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MONTHLY MEAN TIME SERIES OF TEMPERATURE AND SALINITY IN MONTEREY BAY, 1951-1991

by

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December, 1991

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(2) Annual cycle of monthly regression T-S curves, obtained by least-squares method, showed "seasons" cycle in the Bay; and missing salinity data can be filled by regression equations of salinity on temperature.

(3) Anomalously high temperature water occured in some years which had two different time patterns. In the upper layer, shallower waters lead in time where as in the deep water, deeper waterts always lead. These two time patterns are believed to be associated with local forcing (weather conditions) and remote forcing (coastal trapped waves) respectively.

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ABSTRACT

Temperature and salinity profile data, collected from different sources over the last four decades (1951-1991), were compiled and processed to obtain monthly mean time series of thermal conditions in Monterey Bay. The results indicate:

(1) Near surface low salinity water intruded into the Bay from offshore during January to April, especially during March.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. PREVIOUS STUDIES

Many studies have been conducted of thermal conditions in Monterey Bay. Skogsberg (1936) carried out oceanographic observations at 23 stations in the canyon and southern shallow areas of Monterey Bay during the five-year interval (1929-1933). As a result of these observations, an annual rhythm of thermal characteristics was first described. Skogsberg defined three seasons of the thermal conditions: Davidson, Upwelling, and Oceanic.

Bolin (1964) conducted weekly hydrographic observations of a single station (36°42'N, 122°02'W) in the Monterey Submarine Canyon for January 1951 through December 1955 and provided some refinement to the descriptions of the three regimes as given by Skogsberg.

Hopkins Marine Station (HMS) of Stanford University sampled from 1950 to 1973 as part of the California Cooperative Oceanic Fisheries Investigations (CalCOFI).

Lammers (1971) compiled the data gathered by Skogsberg (1929-1933), Bolin (1951-1955) and CalCOFI cruises during 1954-1967. This was the first effort at deriving norms for the thermal characteristics of the entire bay over an extended period of time, and made it possible to determine whether the

thermal properties of a specific period of time were anomalous.

Sampling in the Bay continued during 1974 to 1978 by Moss Landing Marine Laboratory (MLML) as part of pollution surveys for Association of Monterey Bay Area Governments (AMBAG).

McLain and Thomas (1983) assembled CalCOFI and AMBAG data at Hopkins station H3 (36°46'N, 122°01'W), located near the mouth of the Monterey Submarine Canyon. Almost a 10-year period with nearly biweekly sampling was available from 1969 to 1978. These data provide good time series resolution at station H3.

B. PURPOSE

Although many studies described the thermal conditions in Monterey Bay, these descriptions are based on limited time periods or only a portion of the Bay. No paper had described the time series of the Bay over 20 years, and no systematic long-term measurements have been made within the interior of the Bay to determine its general thermal conditions and time series variations.

Hence, the primary purpose of this paper is to bring together and synthesize the existing, albeit fragmentary and incomplete data which were collected from 1951 to 1991, to create a view of the Bay thermal conditions for the last four decades.

Assessment of data quality has been an important part in this study. In this regard, all data collected from last four decades were examined first for quality control. It is important that all useful and reliable data are included in the analysis.

C. GENERAL DESCRIPTION OF STUDY AREA

Monterey Bay (Fig. 1) is almost semi-elliptical in shape with wide communication to the open sea located along the central coast of California. It may be defined by a line joining Lighthouse Point at Santa Cruz at the north end of the Bay and Point Pinos at the south end. This inner bay is approximately 42 km long and 16 km wide.

Perhaps the most prominent feature of Monterey Bay is Monterey Submarine Canyon (Martin, 1964). The head of the canyon is approximately 0.2 km wide and lies only 0.3 km from the mouth of the shoreline at Moss Landing, and the canyon bisects the bay almost symmetrically forming northern and southern shelf regions. The canyon extends southwesterly from its head of depth 18 m and increases to a depth of 865 m and 12 km in width at the mouth of the Bay. The northern shelf covers an area of approximately 238 km^2 and gradually deepens from the shoreline to 90 m at the canyon edge. Soquel Canyon, an 8 km long branch of Monterey Submarine Canyon, extends into the northern shelf to approximately 10 km from shore southeast of Soquel Point. The southern shelf covers an area of

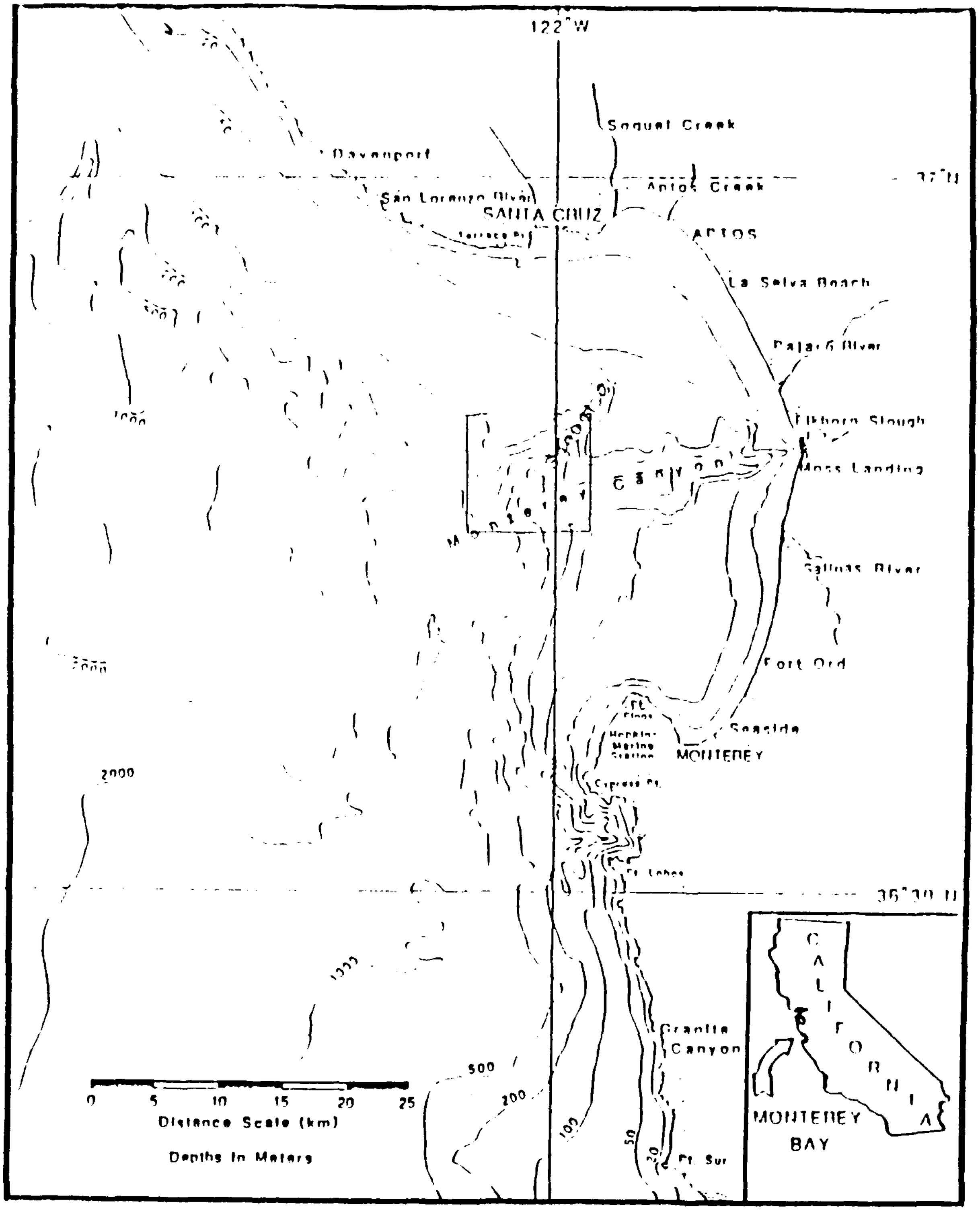

Figure 1 MAP OF MONTEREY BAY (SQUARE SHOWS AREA NEAR STATION H3 WHERE TIME SERIES DATA WERE ANALYZED)

approximately 195 km^2 and is deeper than the northern shelf with a depth of about 180 m at the canyon edge (Smethie, 1973). The southern rim of the canyon runs in a southwest direction and intersects the northern rim of Carmel Canyon south of Point Pinos. Monterey Bay has an area of approximately 534 km^2 of which 433 km^2 (81%) lies over the continental shelf, and 101 km^2 (19%) lies over Monterey Submarine Canyon.

D. CALFORNIA CURRENT SYSTEM

The Calfornia Current system is an eastern boundary current characterized by a wide (about 1000 km), shallow (<500m), slow (about 25 cm/sec) current flowing southward along the western coast of North America (Wooster and Reid 1963). Cool, low salinity, high nutrient Subarctic waters flow southward along the North American coast (Reid, Roden and Wylie 1958). The California Current is part of the eastern gyral in the North Pacific Ocean.

A subsurface current flows northward along the North American coast, known as the California Countercurrent, from Baja California to beyond Cape Mendocino with its core at a depth of about 200 m (Reid, Roden and Wylie, 1958). North of 30°N latitude, its speeds have been measured up to 22 cm/sec, and its width appears to extend to between 50 and 100 km offshore (Reid 1962). Warm, high-salinity Equatorial Pacific

water is transported northward by this current (Sverdrup, Johnson and Fleming 1942).

As the winds shift to the southwest during fall or early winter (Fig. 2), the northward flowing countercurrent becomes stronger and surfaces between Point Conception and British Columbia, and then is known as the Davidson Current. This current persists until February (Bolin and Abbott, 1963) and lies landward of the California Current and extends to approximately 80 km offshore with speed measured between 16 and 47 cm/sec (Reid and Schwartzlose 1962; Schwartzlose 1963).

Interactions of the currents with the seasonal changes of wind field contribute to both the long term and the short term changes in the water mass distribution. During spring and summer, a cell of high atmospheric pressure over the Pacific Ocean and a low pressure cell over western North America are found, resulting in strong winds along the coast primarily northerly and northwesterly (Fig. 2). When strong enough this causes surface water to be transported offshore under the influence of the Coriolis force. Cold, saline water upwells along the coast to replace the surface water transported offshore.

A result of coastal upwelling causes a semi-closed vertical circulation with water moving inshore at some depth, probably less than 200 m, rising to the surface adjacent to the shoreline, and being transported offshore by the wind

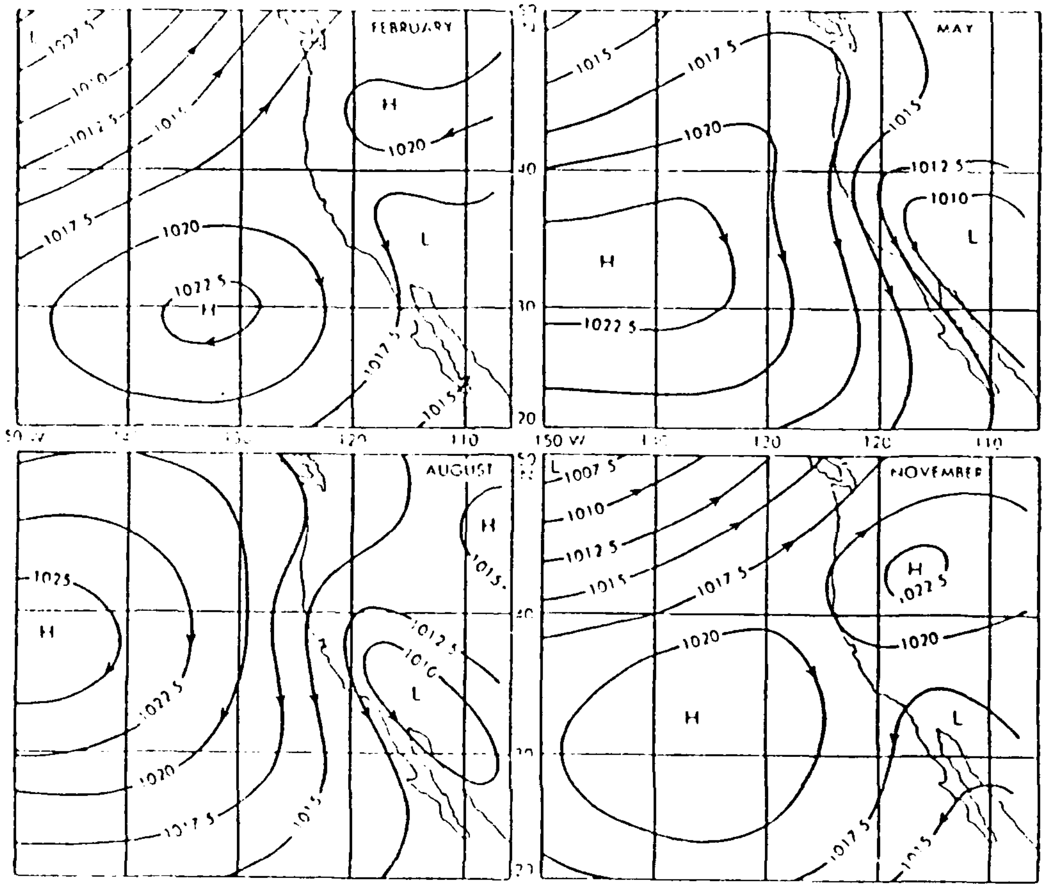

Figure 2 AVERAGE MONTHLY SEA LEVEL PRESSURE OVER THE EASTERN NORTH PACIFIC OCEAN AND WESTERN NORTH AMERICA. (ADAPTED FROM HICKEY 1978)

(Sverdrup and Fleming 1941). Coastal upwelling is estimated at rates ranging from 0.7 m/day to 2.7 m/day and occurs to as far as 50 km offshore (Smith 1968).

In fall and winter the high pressure cell weakens and moves southward, and the low pressure cell becomes intermittent (Fig. 2) (Reid, Roden and Wylie 1958). This causes in a period relatively little wind in the fall and westerly and southwesterly winds north of Point Conception in

the winter (Smith 1968). The Davidson Current develops in late fall and is strengthened during periods of southwesterly winds. Surface water is transported to the right of the wind under the influence of the Coriolis force, resulting in convergence of this water along the coast and subsequent sinking (Bolin and Abbott 1963).

During periods of upwelling, water adjacent to the California coast is low in temperature and oxygen content and high in salinity and nutrient content as the result of subsurface water being brought to the surface.

E. SEASONAL CHANGES IN MONTEREY BAY

Three oceanographic periods have been described to occur in Monterey Bay:

1. The Davidson Current Period

This period is commonly considered to occur from November to February. The influx of warmer waters into the Bay results in a weakening of the vertical temperature gradients and a resulting well-mixed layer of water from the surface to about 50 m (Lammers 1971).

2. The Upwelling Period

This is considered to occur from February to September when southerly longshore winds cause strong upwelling and offshore transport of surface waters. Cold, upwelling waters, can be detected as deep as 700 m; however, water reaching the surface may come from only 200 m or less

(Skogsberg 1936). The vertical currents associated with upwelling in Monterey Bay have been estimated to average 1.5 m/day (Skogsberg 1936).

3. The Oceanic Period

This period is commonly considered from September to November when longshore winds relax and upwelling ceases. Dense, previously upwelled water sinks, and offshore surface water flows onshore marking the beginning of the oceanic period. This transition is often ill-defined, and at times, oceanic water only partially invades the bay with a temperature interface between cool, recently upwelled bay water and warm oceanic water (Skogsberg 1936). During this period, high vertical temperature gradients occur in the upper layer of 100 m.

II. DATA COLLECTION AND PROCESSING

A. AREA SELECTION FOR TEMPORAL AND SPATIAL DISTRIBUTION

All available temperature and salinity profile data were assembled for the region between latitudes 36°30'N and 37°N and east of longitude 122°20'W. All the data covered in this area were compiled over the 41-year interval from 1951 through 1991. The data were used to determine the spatial distribution of conditions in the region.

Due to lack of observations in continuing monthly time series within the Bay for all stations, a smaller area, shown in square box near the center of the Canyon (Fig. 1), was selected as it contained the greatest number of profiles, including Hopkins H3 station. This area is of latitude between 36°45'N and 36°50'N and longitude between 121°58'W and 122°05'W. All the data covered in this small area, based on the most time series area in the Bay, was assumed to be effectively located at its center and represented the long-term time series of that location.

B. DATA COLLECTION

1. Data From NODC

National Oceanographic Data Center (NODC) maintains a computer archive of oceanographic data through the world's oceans. In the past, access to these data has been difficult

but recently, over 1.4 million subsurface temperature-salinity profiles for the Pacific Ocean have been published on Compact Disc - Read Only Memory (CD-ROM) optical discs (NODC 1989). Accompanying software support data search, extract and tutorial capabilities, which allow the data to be read, but not altered, on a personal computer. CD-ROMs can store over 600 MB of data and are emerging as an economical and innovative medium for data publishing and distribution.

Data extracted from the NODC CD-ROM in the Bay covered the years between 1939 and 1988 but only the data between 1951 and 1988 were used due to erratic and sparse data in the early years.

The NODC data were derived from NODC's six major temperature and salinity profile data files:

(1) Oceanographic station (Nansen cast) data (SD2);

(2) Low-resolution conductivity/salinity-temperature-depth (C/STD) data (c/STD with parameter values at selected depths derived from original high resolution profiles);

(3) Mechanical bathythermograph (MBT) data;

(4) Expendable bathythermograph (XBT) data;

(5) Selected-level bathythermograph (SBT) data (XBT data submitted to NODC at user-specified depths rather than at inflection points); and

(6) IGOSS radio message bathythermograph (IBT) data.

Data extracted from the NODC CD-ROM in the Bay area had a distribution for whole period of years as shown in Table I:

Table I DISTRIBUTION OF NODC DATA IN MONTEREY BAY

YEAR	MBT	XBT	STD	SD2	SBT	IBT	TOTAL
51	93	0	0	40	0	0	133
52	201	0	0	58	0	0	259
53	162	0	0	46	0	0	208
54	105	0	0	49	0	0	154
55	88	0	0	45	0	0	133
56	86	0	0	0	0	0	86
57	5	0	0	0	0	0	5
58	1	0	0	0	0	0	1
59	30	0	0	0	0	0	30
60	0	0	0	3	0	0	3
61	3	0	0	4	0	0	7
62	1	0	0	1	0	0	2
63	76	0	0	0	0	0	76
64	233	0	0	1	0	0	234
65	226	0	0	3	0	0	229
66	226	0	0	1	0	0	227
67	95	0	0	0	0	0	95
68	1	1	0	1	0	0	3
69	0	27	0	8	0	0	35
70	1	59	0	58	0	0	118
71	0	0	0	165	0	0	165
72	0	0	0	4	0	0	4
73	0	3	0	4	0	0	7

YEAR	MBT	XBT	STD	SD2	SBT	IBT	TOTAL
74	0	1	0	0	0	0	1
75	0	4	0	143	0	2	149
76	0	12	0	94	0	0	106
77	0	14	0	0	0	0	14
78	0	0	0	6	0	0	6
79	0	1	0	0	0	0	1
80	0	8	0	0	0	1	9
81	0	1	0	4	0	0	5
82	0	0	0	0	0	0	0
83	0	14	3	0	0	0	17
84	0	31	8	7	0	0	46
85	0	10	2	0	0	4	16
86	0	20	0	0	2	0	22
87	0	1	0	0	1	7	9
88	0	0	0	0	0	16	16
TOTAL	1533	207	13	745	3	30	2531

Surprisingly, only 2531 observations were recorded and stored in CD-ROM by NODC in the Bay for the last four decades, representing a very incomplete portion of the data actually collected.

2. CalCOFI And AMBAG Data Assembled By McLain

Data collected by CalCOFI and AMBAG at station H-3 (Described in Chapter I.) in the 10-year period from 1969 to 1978 were available from the study of McLain and Thomas (1983). The actual data from McLain were measured by Stanford University's Hopkins Marine Station (HMS), Moss Landing Marine

Laboratories (MLML) and Naval Postgraduate School in several expendable bathythermograph (XBT) casts. These data included a total of 291 hydrographic profiles taken from 1967 to 1968.

3. Moss Landing Marine Laboratories Tape

Data collected by MLML has been stored on a 9-track tape in their own format (Broenkow 1990). The data in Monterey Bay was retrieved from the tape using Fleet Numerical Oceanography Center (FNOC) computer. A total of 4048 observations was found for the years 1951 to 1972 with some stations measured at H-3 in same period. This may indicate some of the stations that duplicated each other. Hence, all duplicated data was deleted in the data processing and discussed in next section.

4. Naval Postgraduate School Data (NPS)

18 CTD profiles from two hydrographic stations, near station H-3, were offered by NPS from April of 1988 to February of 1991. These data were collected by one or two months for each profile.

5. MBARI Data

Data from the moored buoy operated by the Monterey Bay Aquarium Research Institute (MBARI), located at 36°45'N, 122°01'W, close to station H-3 were also available. These data are from selected depths and are transmitted almost every day via satellite and received by MBARI. 326 profiles with selected depths up to 300 m were available for August 23, 1989

to October 4, 1990. Due to wrong data received in early months of 1990, most of the data from January through March had been cancelled and no data were available in February.

Finally, 38 CTD's data at H-3 were collected by MBARI from the Point Lobos research vessel. These data were taken almost biweekly from April 1989 to August 1990 but no data were available for May 1989.

C. DATA PROCESSING

Since data came from several different sources, the quality of data was variable. All data had to be examined before using them. Data known to be of questionable quality were not candidates for the further analysis and were eliminated. In addition, data selected for further use were passed through a rigorous statistical screen, eliminating all possible bad data levels of the available profile observations.

As the data were being selected and reviewed for further research, considerable variation in the temperature and salinity value ranges within the Bay was noted. These variations suggested positional errors in the data or, in the case of radio message data (IBT and Mooring data), erroneous encoding/transmission of values. To eliminate these questionable profiles, statistical files of temperature and salinity were computed for all of available data.

The data from NODC had been quality controlled, based on statistical parameters for the ten-degree square area. If parameter values (either temperature or salinity) at any depth level were farther than four standard deviations from the mean, the entire cast or station was deleted. This is a coarse quality evaluation for a small area less than one half-degree area like Monterey Bay. Further rigorous quality control were needed for all profiles to prepare the data for analysis. The assembled data were examined by following procedure:

1. Reformat The Data

Data from different sources were in different formats. Hence, data had to be reformated before they could be merged, sorted and processed together. The data were converted to a common format, based on the author's convenience, research purpose and ease of processing.

2. Mapping Conditions Over The Whole Bay

After the above quality control checks were made, the data were merged and separated into 12 monthly files. Maps were made of the distribution of temperature and salinity over the entire Bay area. The data were averaged over 1 minute squares for contour mapping of temperature (Fig. 13-15). Insufficient data were available for salinity and the data were not contoured (Fig. 24-35). Due to the large spatial

variations near shore, only profile data in the small square area (Fig. 1) were used in further analysis.

3. Statistical Checks

After conversion to a common format, basic statistical parameters were computed for each depth level and month. These parameters were:

(1) Minimum value

(2) Maximum value

(3) Total number of values

(4) Mean value

(5) Standard deviation

(6) Depth of observation

Not only depth, temperature and salinity but also time and location were checked by these parameters. Using these tests, many obvious errors were detected, such as month or day values out of range, location on the land, depth deeper than bottom of sea and anomalous low or high values of temperature or salinity. Profiles that had such obvious errors were deleted.

4. Duplicate Checks

Because the data from NODC and McLain were from published sources, many duplicates occurred between them. A program was written and checked to compare the date and position first and then depth, temperature and salinity values. This procedure delected many duplicates in MLML's

data and McLain's data from 1969 to 1972. Similarly, many of the NODC's SD2 data and MLML's data duplicated each other. All duplicate data were deleted. In cases of near duplicates (position off by a minute) the most reasonable cast was retained.

5. Profile Plot Examination

Temperature profiles, salinity profiles and temperature-salinity (T-S) profiles were plotted for each monthly data file. These curves were useful for checking data to determine if individual data points might be in error. If a point was far from the expected curve for the region, it was regarded with suspicion (Pickard and Emery 1982). In most cases, any data point which exceeded two standard deviations from the mean for that month and depth was deleted.

The composite temperature profiles are shown in Figure 3 for each month before corrections. Many erroneous points are evident in January, March, April, May, June, October and December. All individual error points and unexpected points were either fixed by linear interpolation or deleted. In figure 3 many profiles can be seen that appear too warm at depth and which extend to only 200 m. These profiles are all MBT casts during the 1950's. The MBT data all appear of low quality and were screened using case by case check. Many of the MBT data sets and some of the profiles that exceeded two standard deviations were deleted in this process. Figure 4

shows the temperature profiles after corrections; these good quality data would be used for further analysis and discussed in next chapter.

The salinity profiles were similarly edited and are shown in Figure 5 in every month before corrections. Many profiles had either too low or too high salinity values which exceeded two standard deviations. Again, those profiles were deleted, and Figure 6 shows the profiles after corrections. Finally, T-S diagrams were plotted for each month before and after corrections separately (Figures 7 and 8).

During the quality control process, deleted temperature profiles would delete the entire cast while deleted salinity profiles would keep their temperature profiles if they were good. Hence, more salinity data had been deleted. Table II summarizes the profiles rejected during quality control processing.

Table II indicates that about 28 percent of MBT data were rejected due to lower quality mainly and about 41 and 28 percent of SD2 and McLain data were rejected due to duplicate profiles mainly with MLML's data. The other data were rejected due to bad data. No profiles were rejected in recent years, indicating either good quality due to improved instruments or data had been quality controlled before collected in this study. The total number of profiles in the small square area was 1546. These were 25 percent of all those available for the entire bay area; all these clean data

would be used for temporal analysis and discussed in next chapter.

Table II NUMBERS OF PROFILES BEFORE AND AFTER QUALITY CONTROL PROCESSING

DATA FROM	YEARS	NUMBER BEFORE QC	NUMBER AFTER QC	NUMBER REJECT-ED	REJECT -ED %	WITHIN SMALL AREA
SBT	1986-87	3	3	0	0	0
MBT	1951-70	1533	1112	421	28%	243
XBT	1968-87	207	202	5	3%	45
IBT	1975-88	30	29	1	3%	6
STD	1983-85	13	13	0	0	4
SD2	1951-84	745	436	309	41%	89
McLain	1967-78	291	210	81	28%	210
MLML	1951-72	4048	3902	146	4%	567
NPS	1988-91	18	18	0	0	18
MOOR-ING	1989-90	326	326	0	0	326
MBARI CTD	1989-90	38	38	0	0	38
TOTAL	1951-91	7252	6289	963	13%	1546

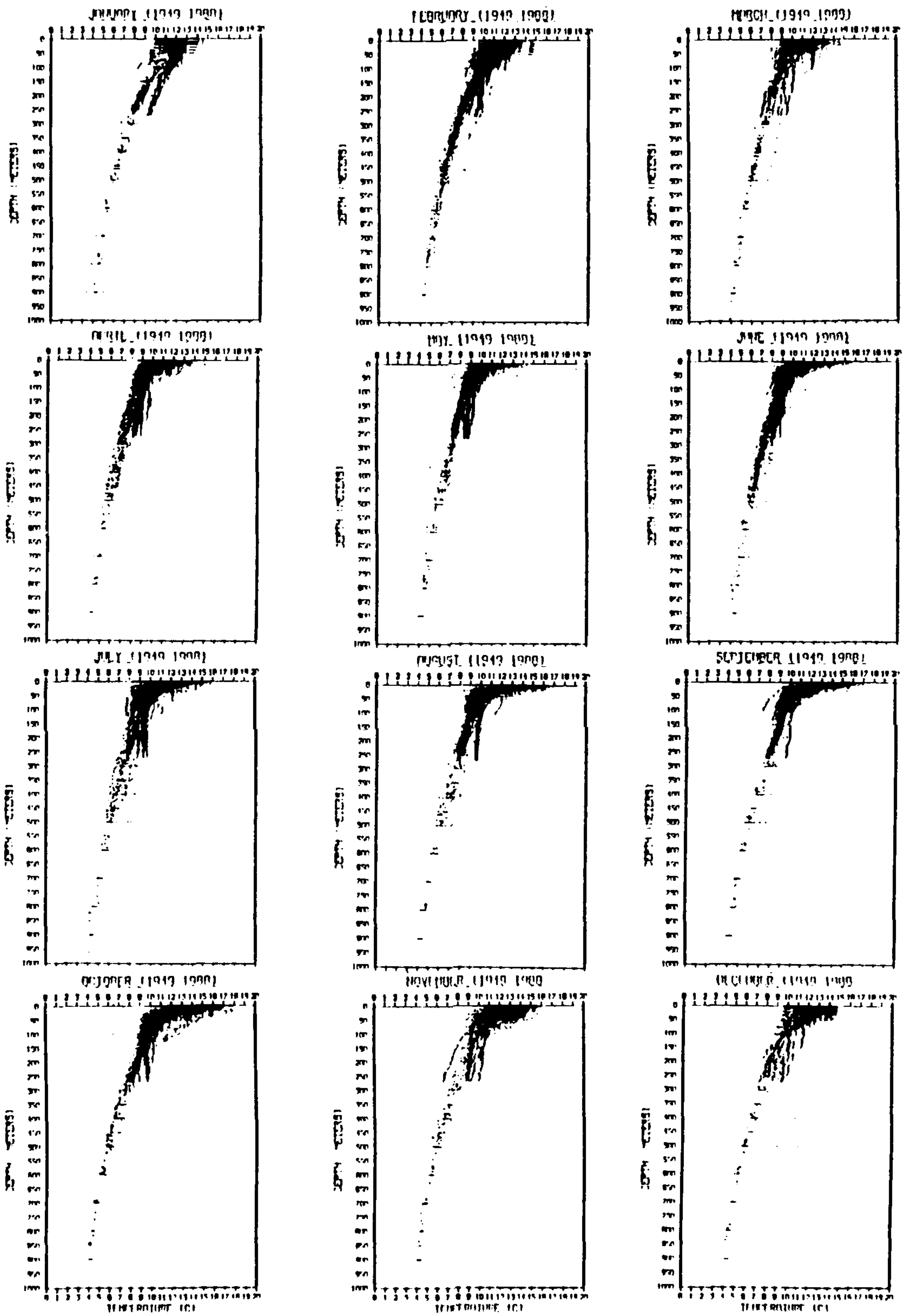

Figure 3 TEMPERATURE PROFILE DATA BEFORE CORRECTION

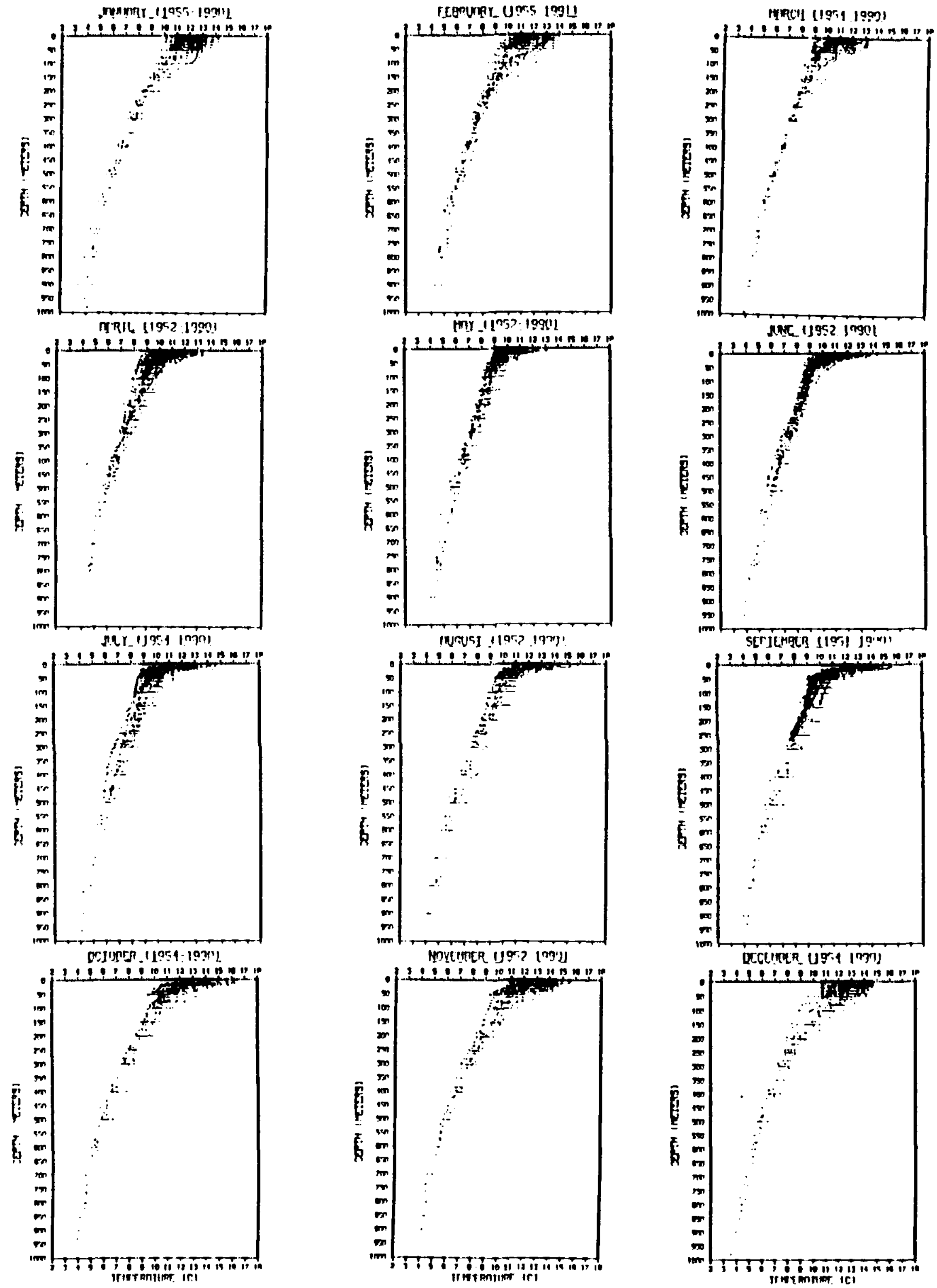

Figure 4 TEMPERATURE PROFILE DATA AFTER CORRECTION

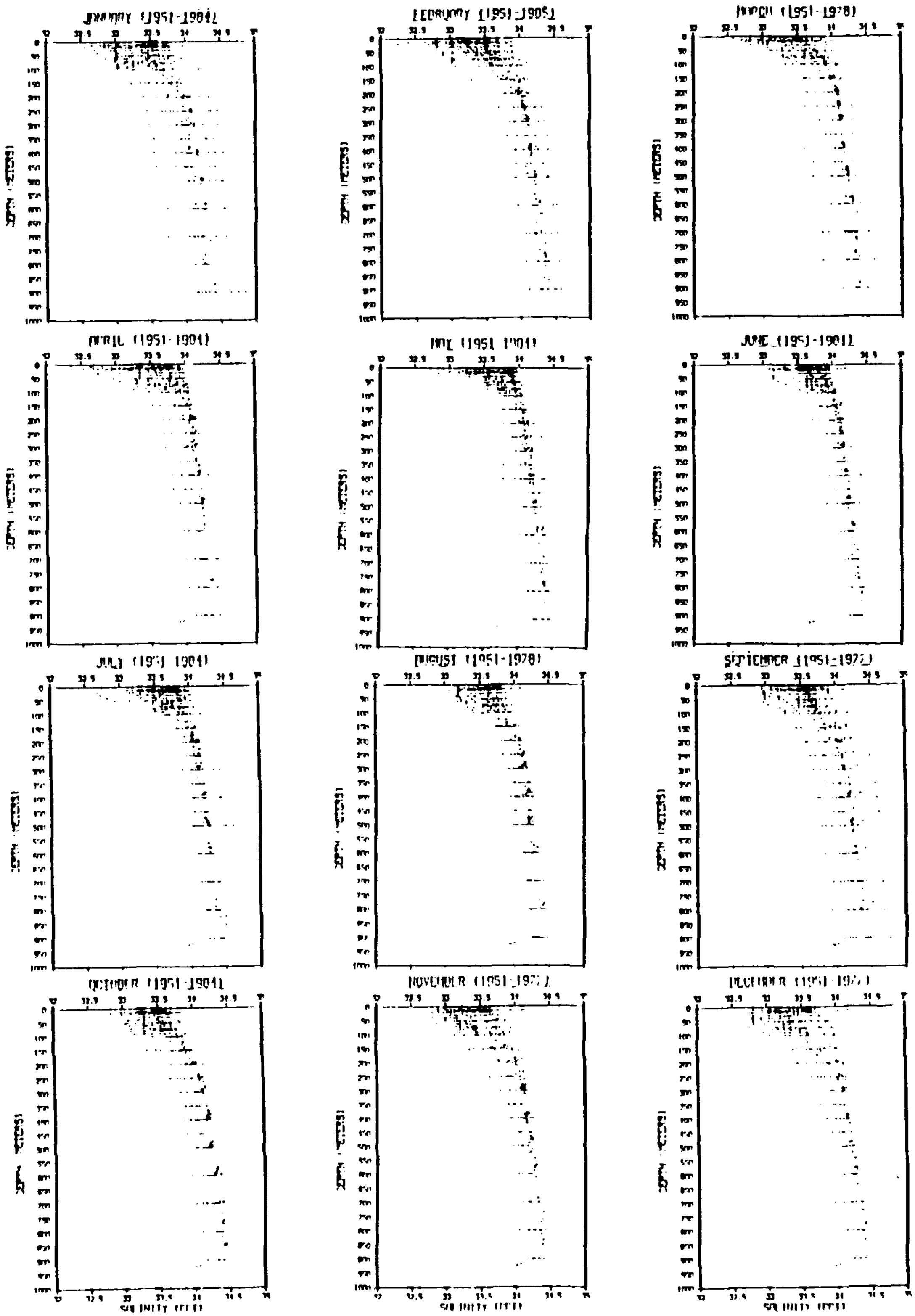

Figure 5 SALINITY PROFILE DATA BEFORE CORRECTION

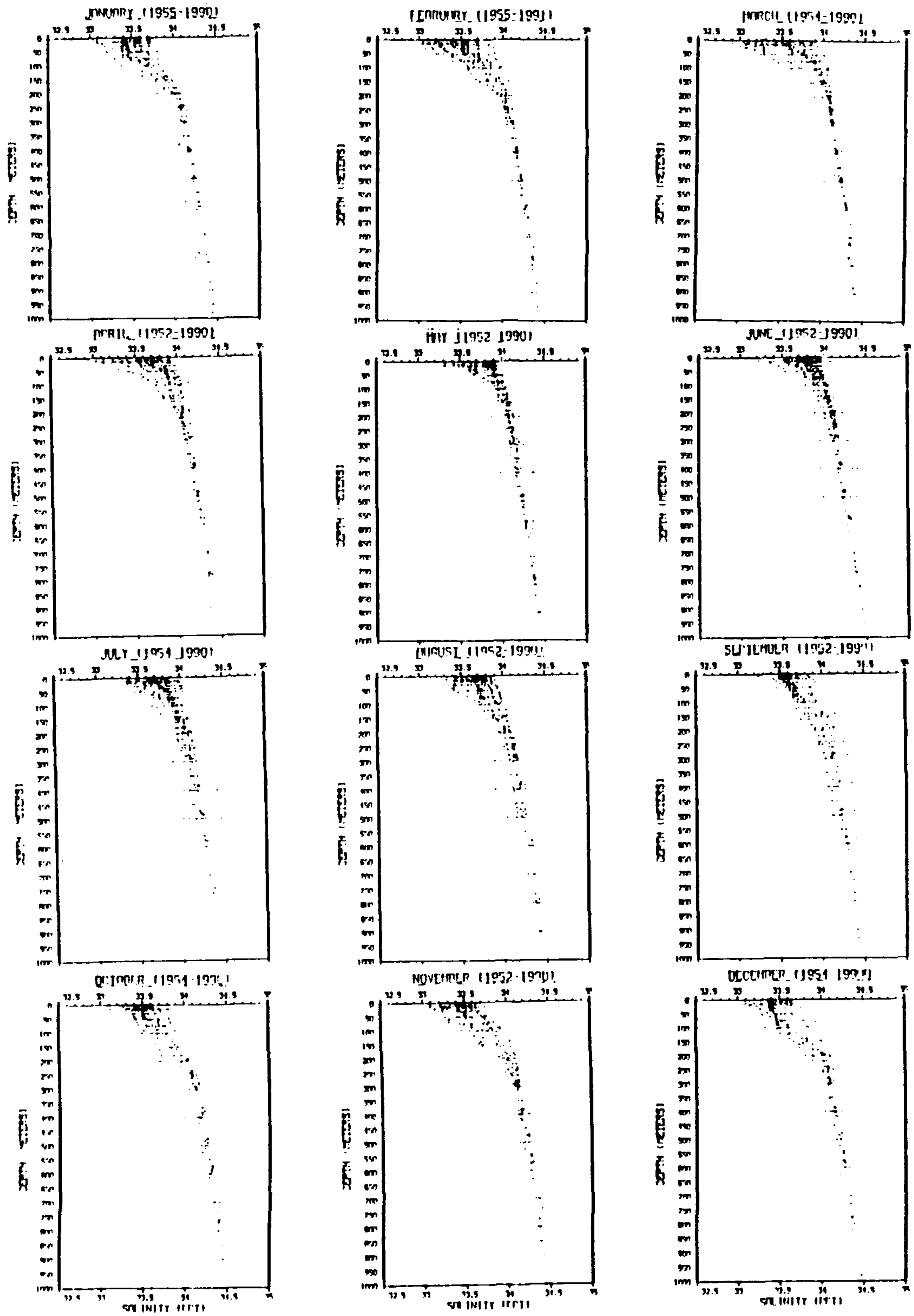

Figure 6 SALINITY PROFILE DATA AFTER CORRECTION

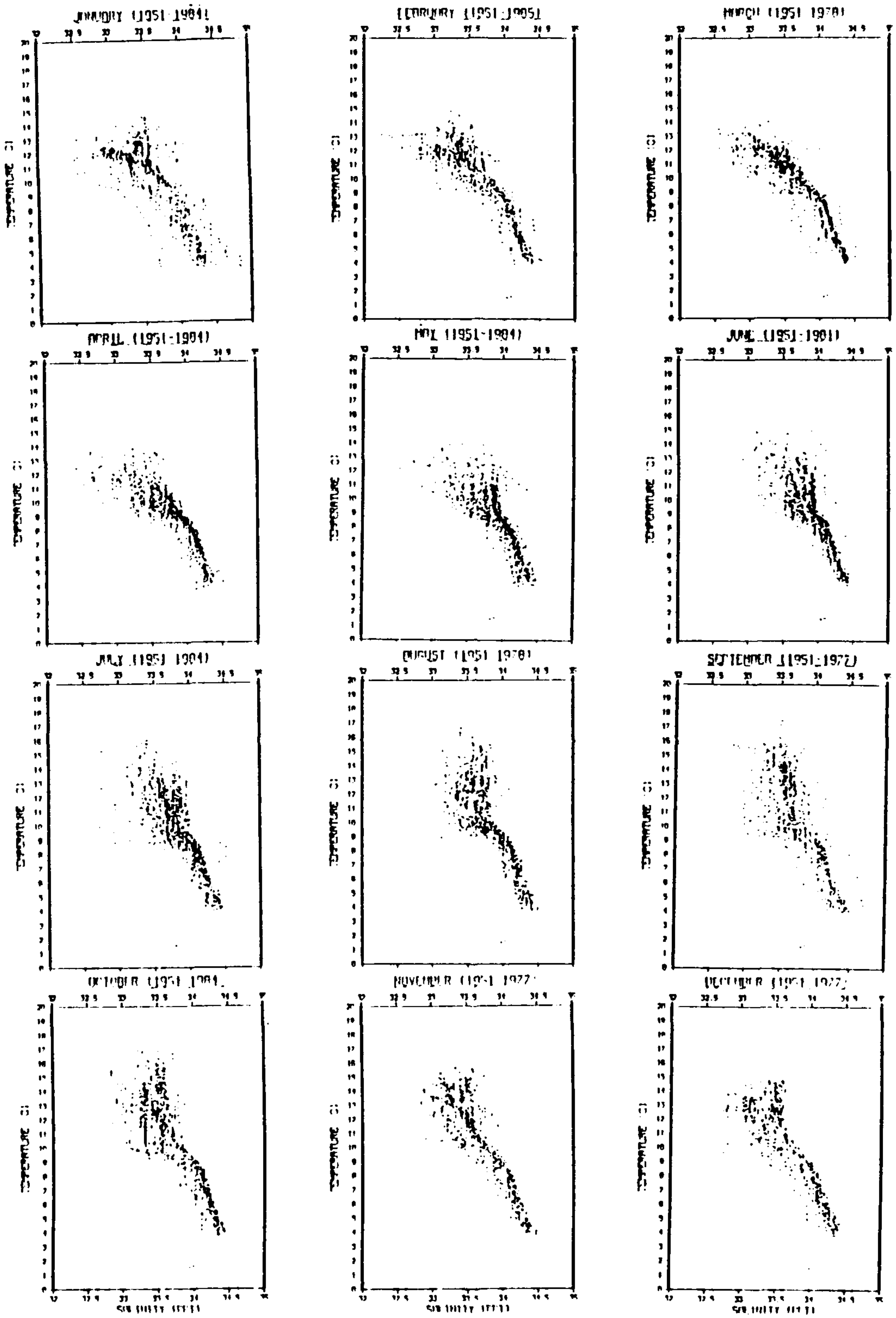

Figure 7 T-S PLOT BEFORE CORRECTION

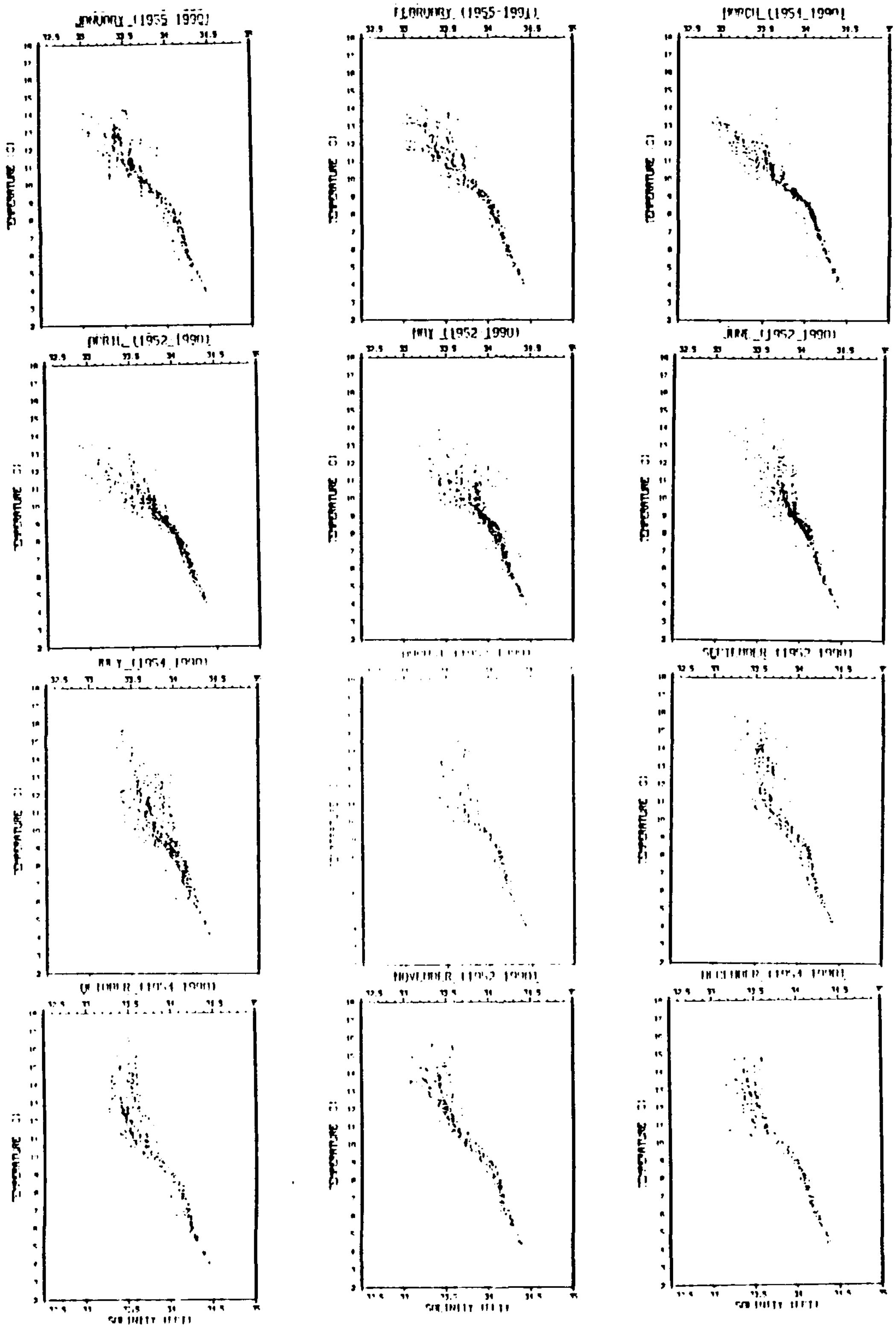

Figure 8 T-S PLOT AFTER CORRECTION

III. RESULTS

A. THE CHARACTERISTICS OF WATER MASS IN MONTEREY BAY

Figure 8 shows the annual cycle of T-S plot for each month. The plots indicate that low salinity and high temperature water occurred in the upper layer, and high salinity and low temperature water appeared in the deep water. In general, this indicated a very stable water column in Monterey Bay through the annual cycle.

1. T-S Curve Fitting

A series of polynomial regression equations of temperature and salinity were computed for each month to summarize the T-S curves. These equations can also be used to estimate missing salinity data in computing density or dynamic height (instead of using a constant value) and to analyze the water mass characteristics for every month.

To determine an equation of T-S curve, observe the scatter diagrams in figure 8. All diagrams indicated that there was not a linear relationship between temperature and salinity. It was often possible to visualize a smooth curve that approximated the data. Hence, a polynomial of the three degrees may be appropriate to describe an equation of the approximating T-S curve. Assume that salinity is a function of temperature which can be written as follows:

$$S = F(T) = AT^3 + BT^2 + CT + D \tag{1}$$

Where S = Salinity

T = Temperature

A, B, C and D = Coefficents to be determined

From observations of n pairs of salinity and temperature values, we have

$$\begin{aligned} S_1 &= AT_1^3 + BT_1^2 + CT_1 + D \\ S_2 &= AT_2^3 + BT_2^2 + CT_2 + D \\ &\vdots \\ S_n &= AT_n^3 + BT_n^2 + CT_n + D \end{aligned} \tag{2}$$

Which can be rewritten in matrix form as follows:

$$\begin{bmatrix} T_1^3 & T_1^2 & T_1 & 1 \\ T_2^3 & T_2^2 & T_2 & 1 \\ & \vdots & & \\ T_n^3 & T_n^2 & T_n & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_n \end{bmatrix} \tag{3}$$

Equation 3 can be simply rewritten as:

$$T_{n\times 4}\, X_{4\times 1} = S_{n\times 1} \tag{4}$$

Where T = known n×4 matrix and n>4

X = unknown 4×1 matrix to be determined

S = known nx1 matrix

Equation 4 showed more equations than unknowns. In the case TX = S is inconsistent, the least-squares methods were used to solve this system (Eq. 4). Intuitively, the least-squares approach is to determine a vector Xlsq (least-squares vector X) such that $\|TX-S\|$ (norm or length) is minimized for X=Xlsq. Geometrically, we must find the vector in the subspace spanned by the columns of matrix T that is closest to vector S (Eq. 3). The subspace spanned by the columns of matrix T is called the column space of T or the rank of T and will be denoted R(T). Let Z be any vector in R(T). Then Z is a linear combination of the columns of T:

$$Z = t_1 \times col_1(T) + t_2 \times col_2(T) + t_3 \times col_3(T) + t_4 \times col_4(T) \tag{5}$$

Let

$$t = [t_1 \ t_2 \ t_3 \ t_4]' \tag{6}$$

Then equation 5 can be written as:

$$Z_{n\times 1} = T_{n\times 4} \ t_{4\times 1} \tag{7}$$

Intuitively we can not get closer to S in R(T) than the distance from S to P = $proj_T S$ (the projection of S onto T). Thus the least-squares solution Xlsq is such that

$$T_{n\times 4}\, X1sq_{4\times 1} = P_{n\times 1} \tag{8}$$

It also follows that S-P should be orthogonal to R(T). This orthogonality condition between S-P and R(T) establishes an important relationship between S and Xlsq. It follows that since Z and S-P are orthogonal, then their multiplication is equal to zero as follows:

$$0 = Z'(S - P) = (Tt)'(S - T * X1sq) = t'(T'S - T'T * X1sq) \tag{9}$$

for every choice of t in R^4 (4 dimensional). The only vector in R^4 orthogonal to every other vector is the zero vector; thus

$$T'S - T'T * X1sq = 0 \tag{10}$$

It follows that the least-squares solution of equation 4 satisfies:

$$T'T * X1sq = T'S \tag{11}$$

The system

$$T'TX = T'S \tag{12}$$

is called the normal equations of the least-squares problem associated with linear system TX=S. A solution to the normal equations will be a least-squares solution of TX=S. That is

$$Xlsq = (T'T)^{-1} T'S \qquad \textbf{(13)}$$

The expression from equation 13 and the data from figure 8 were used to yield monthly polynomial equation (Eq. 1) for salinity. They are

$$S_1 = 0.002558T_1^3-0.071841T_1^2+0.513478T_1+33.228206 \qquad \textbf{(14)}$$

$$S_2 = 0.002493T_2^3-0.071632T_2^2+0.515930T_2+33.219119 \qquad \textbf{(15)}$$

$$S_3 = 0.001125T_3^3-0.037226T_3^2+0.224592T_3+34.035841 \qquad \textbf{(16)}$$

$$S_4 = 0.002075T_4^3-0.062405T_4^2+0.452636T_4+33.338635 \qquad \textbf{(17)}$$

$$S_5 = 0.002185T_5^3-0.058329T_5^2+0.378802T_5+33.638088 \qquad \textbf{(18)}$$

$$S_6 = 0.000703T_6^3-0.017068T_6^2+0.030462T_6+34.541121 \qquad \textbf{(19)}$$

$$S_7 = 0.000270T_7^3-0.004300T_7^2-0.087760T_7+34.878379 \qquad \textbf{(20)}$$

$$S_8 = 0.001604T_8^3-0.040953T_8^2+0.223670T_8+34.068633 \quad \textbf{(21)}$$

$$S_9 = 0.001115T_9^3-0.028354T_9^2+0.122389T_9+34.314461 \quad \textbf{(22)}$$

$$S_{10} = 0.001648T_{10}^3-0.043870T_{10}^2+0.251436T_{10}+33.990565 \quad \textbf{(23)}$$

$$S_{11} = 0.002434T_{11}^3-0.068802T_{11}^2+0.491501T_{11}+33.291585 \quad \textbf{(24)}$$

$$S_{12} = 0.002799T_{12}^3-0.076245T_{12}^2+0.532984T_{12}+33.216599 \quad \textbf{(25)}$$

The subscripts in equations 14-25 represent months. Figure 9 shows the T-S curves for every month based on the equation 14 through 25 (Note: Figure 9 does not use the actual surface temperature data). From the average long-term time period point of view, the water type (Fig. 9) indicates that at temperatures lower than about 8°C and salinities greater than about 34‰, there was not much change through the whole year. These were at depths of 200 m depth or deeper which had such characteristics of water type in Monterey Bay. This may indicate that the short-term fluctuations in the deep water (about >200m) may occur, but always tend to back to the original water type, this is stable case. Hence, such water type dominated through whole period in deep water and were not

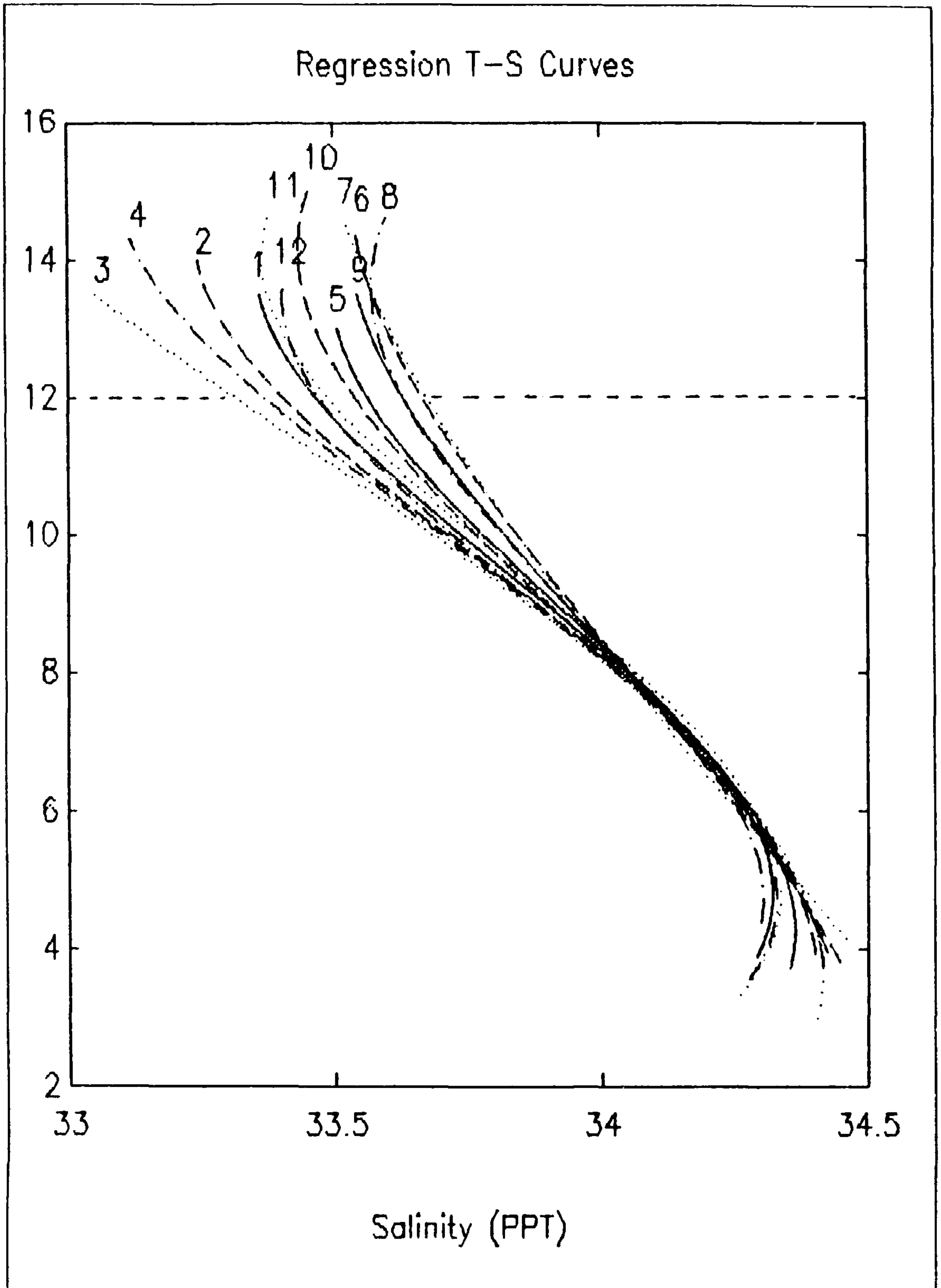

Figure 9 REGRESSION T-S CURVES

effected by season. But, there are some fluctuations in very deep water (about >750 m) which are associated with temperatures lower than 6°C, these are artifacts associated with the regression procedure.

Figure 9 also showed the regression T-S curves in the upper layer (<200m) that had seasonal change. There were three groups of water type at 12°C (about surface to 60 m depth) along the cross dash line (Fig. 9). It was understood that the Upwelling Period started in March and became stronger rapidly in May when southerly longshore winds began stronger (see Fig. 2). The upwelling period continued until July, and then weakened and ceased in August. High salinity is observed during this period. During fall transition, from August through October, in the Oceanic Period, dense, previously upwelled water sinks, offshore surface water flows onshore and corresponding to the period of weaker and variable winds, marking the beginning of the oceanic period. During the Davidson Current period from November through February, warm, high salinity and low thermal gradient of water type occurs. The month of March might be expected as a spring transition period; cold and low salinity water near the surface was found. It may be indicated that cold and low salinity water from offshore intruded into the Bay, when the winds changed and the Davidson Current became undercurrent during the spring transition period.

Figure 9 indicats that the periods associated with each of Skogsberg's (1946) three "seasons" were somewhat different. For example, in Figure 9 of T-S plot suggested that the Davidson Current Period extended from November to February (versus mid-November to mid-February); the Spring Transition Period might be expected in March (no particular mention in Skogsberg); the Upwelling Season, from April to July (versus mid-February through late August); and the Oceanic Period, from August to October (versus late August to mid-November). Table III shows the T-S's and Skogsberg's seasonal period in Monterey Bay.

Table III SEASONAL PERIOD IN MONTEREY BAY

Period	T-S	Skogsberg
Upwelling	Apr.-Jul.	mid Feb.-late Aug.
Oceanic	Aug.-Oct.	late Aug.-mid Nov.
Davidson	Nov.-Feb.	mid Nov.-mid Feb.
Spring	March	no mention

Skogsberg's seasonal description was based mainly on temperature data acquired over 5 years at several fixed locations and along several transects in the southern half of Monterey Bay. This seasonal description has been questioned on several occasions (e.g., Barham 1956) and was expanded upon by Bolin and Abbott (1963).

The seasonal breakdown described on this paper was based on water mass analysis; in fact, different water types were found in the Bay. So, this might be a very important factor to define "seasonal" differences. Breaker (1989) suggested that seasonal breakdown in the Bay should use water mass analysis.

2. The Annual Cycle Of Temperature And Salinity In Monterey Bay

Figure 10 shows the mean annual cycle of temperature in the analysis area, and Figure 11 (adapted from Lammers 1971) shows the mean annual cycle of temperature in the Canyon area in another period (1929-1968). The two figures are generally similar in shape. Based on the data shown in Figure 10, the upwelling period occurs from late February to late July; the oceanic period from early August to October which had high gradient temperature in upper 50 meters; and the Davidson Current period occurs from November to February when well-mixed and weakening in temperature gradient occurs in the upper layer. The spring transition period is not well defined in either Figure 10 and 11.

The mean annual cycle of salinity in the analysis area is shown in Figure 12. Low salinity occurs from November through April near the surface. Due to the transition of wind pattern during this period, this may indicate that the low salinity water from offshore intrudes into the Bay.

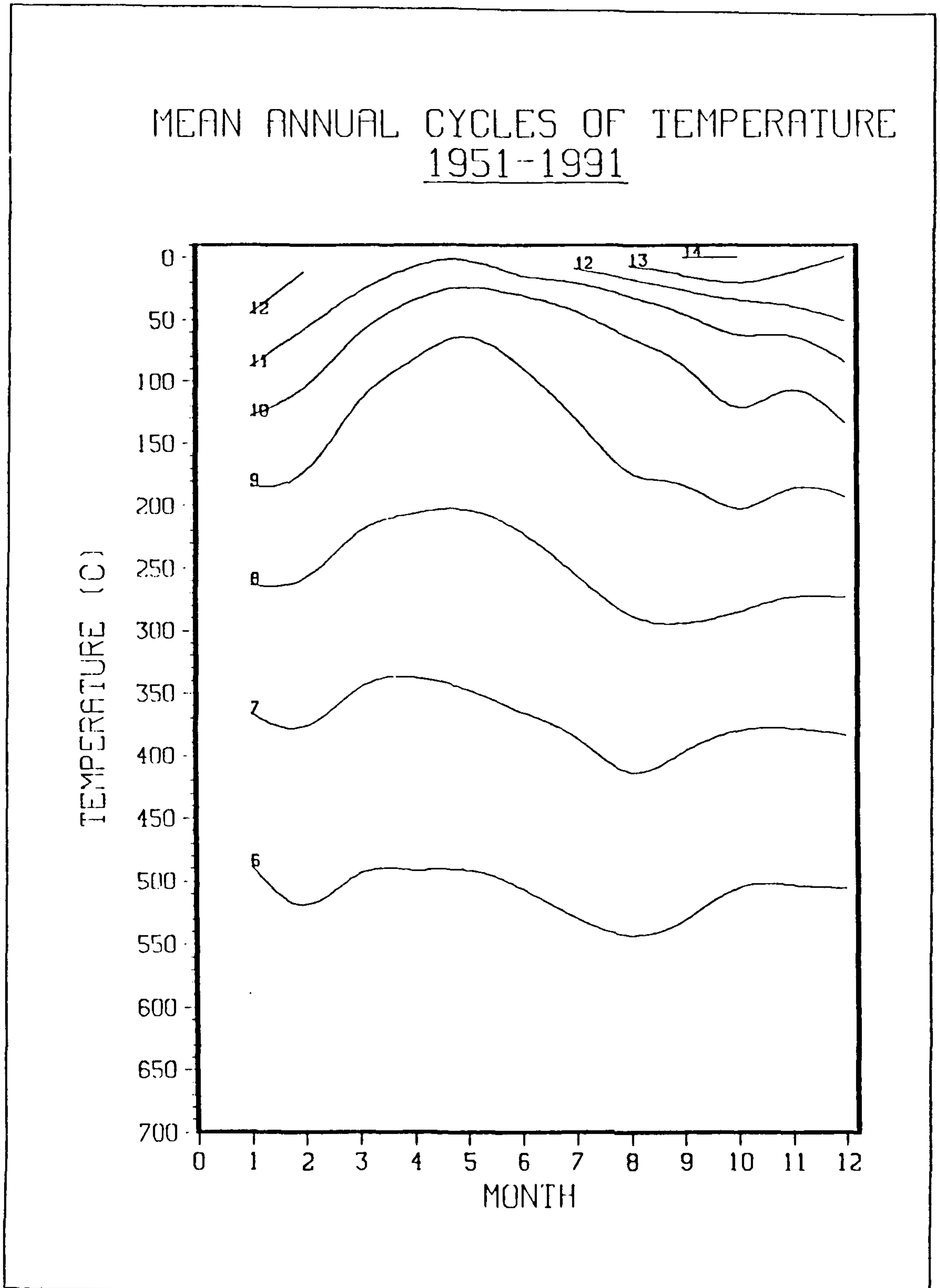

Figure 10 MEAN ANNUAL CYCLE OF TEMPERATURE (1951-1991)

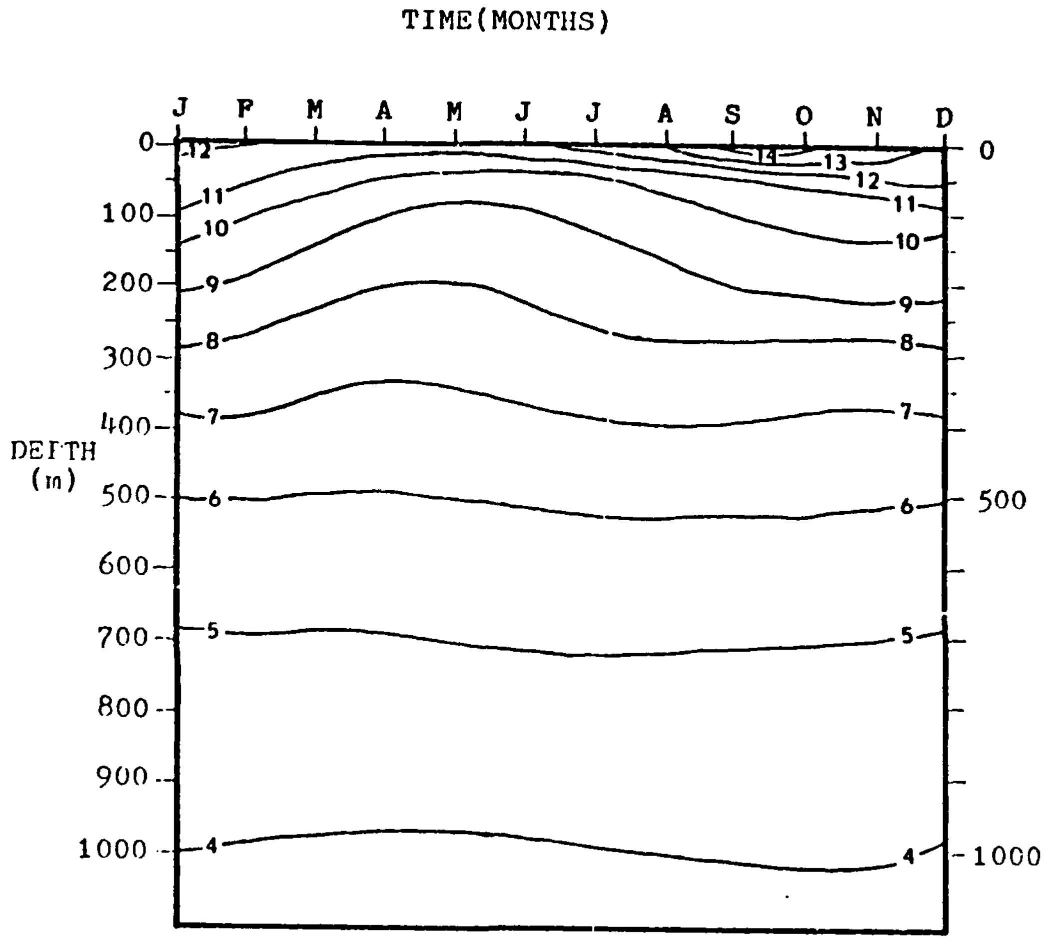

Figure 11 MEAN ANNUAL CYCLE OF TEMPERATURE (1929-1968) (ADAPTED FROM LAMMERS 1971)

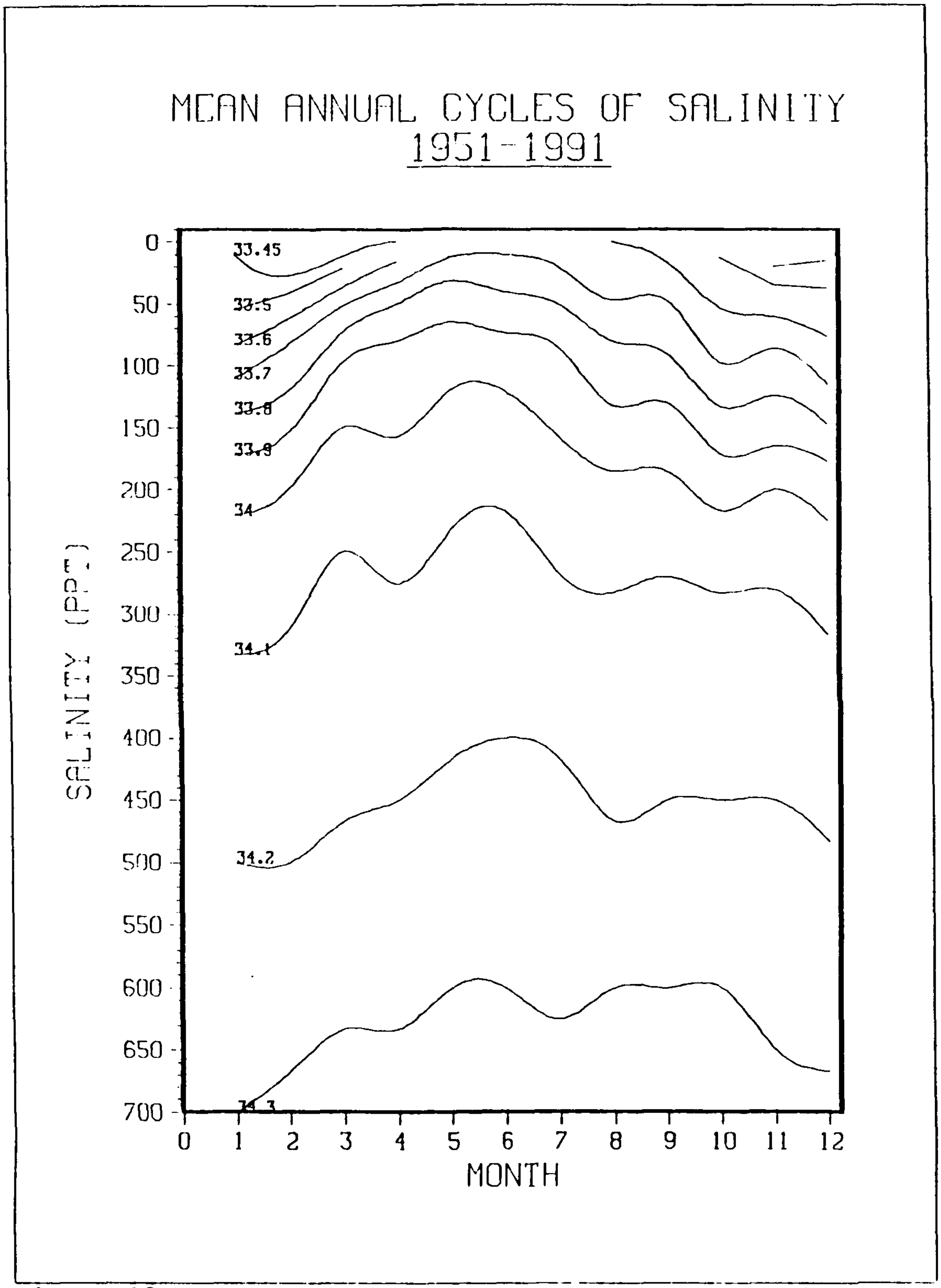

Figure 12 MEAN ANNUAL CYCLE OF SALINITY (1951-1991)

Salinity (Figure 12) has a similar cycle as temperature (Figure 10) except in the deeper waters. Both figures demonstrate that the internal density structure oscillates vertically to depth of 500 m or more. But as indicated by Skogsberg, upwelling at depths considerably greater than 300 m is not due to local wind-forcing. These deep variations in the density field may reflect variations in the California Current and Undercurrent and not be closely coupled with local processes.

B. HORIZONTAL DISTRIBUTIONS OF MONTHLY MEAN SEA SURFACE TEMPERATURE AND SALINITY IN MONTEREY BAY

The distribution of monthly mean sea surface temperature over Monterey Bay is shown in Figures 13-15. These figures were made by averaging all available data by 1 minute squares over the Bay. Mean values were computed for each area with three or more values and are represented by dots in the figures. Although the fields were relatively sparse, the fields were contoured to show mean patterns of temperature and salinity over the Bay. Dashed lines represent probable extensions of the contour lines.

1. Upwelling Period

The coldest waters in the Bay occurred during the period from March to May. Figures 13-14 show the intrusion of the colder waters from seaward. It appeared that the main intrusion broadly occurred along the axis of the Canyon (note

the 11°C and 12°C isotherms in March, April and May). April might be the coldest month of the year over Monterey Bay, but a tongue of cold water (see 11°C isotherm) in May intruded deeply into the mouth of the Submarine Canyon over entire month; this phenomenon coincided with the upwelling period. It might indicate that the strongest upwelling occurred in May. Indeed, the T-S plot (Fig. 9) appeared the strongest rate increasingly in May, and mean annual cycle of temperature plot (Fig. 10) showed the same pattern in the upwelling period.

2. Horizontal Temperature Gradients

Sea surface temperature gradients were weakest during the winter period from November through February with nearly uniform temperature throughout the Bay, less than 0.5°C change occurred in January. The uniform temperature characterizing this period are probably due to the influx into the Bay of warmer waters from the north-flowing Davidson Current (prevailing during the above period) and winter cooling. In March, the horizontal temperature gradients became stronger and continued to increase in strength until reaching their annual maximum in June-July; strength due to contrast between warming and upwelling. Steady weakening of temperature gradients occurred from August until February, completing the annual cycle.

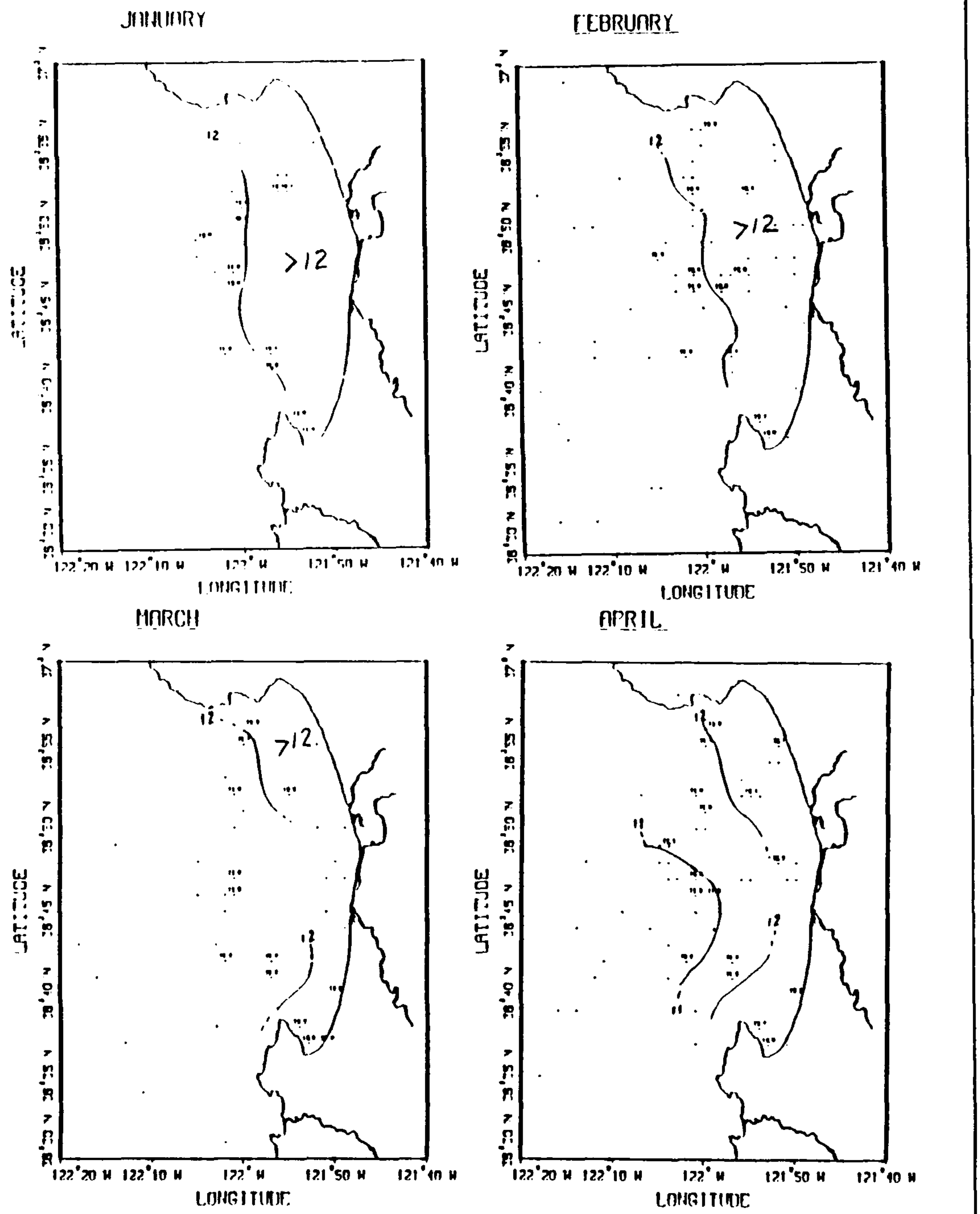

Figure 13 DISTRIBUTION OF THE MEAN MONTHLY SEA SURFACE TEMPERATURE FOR JANUARY THROUGH APRIL

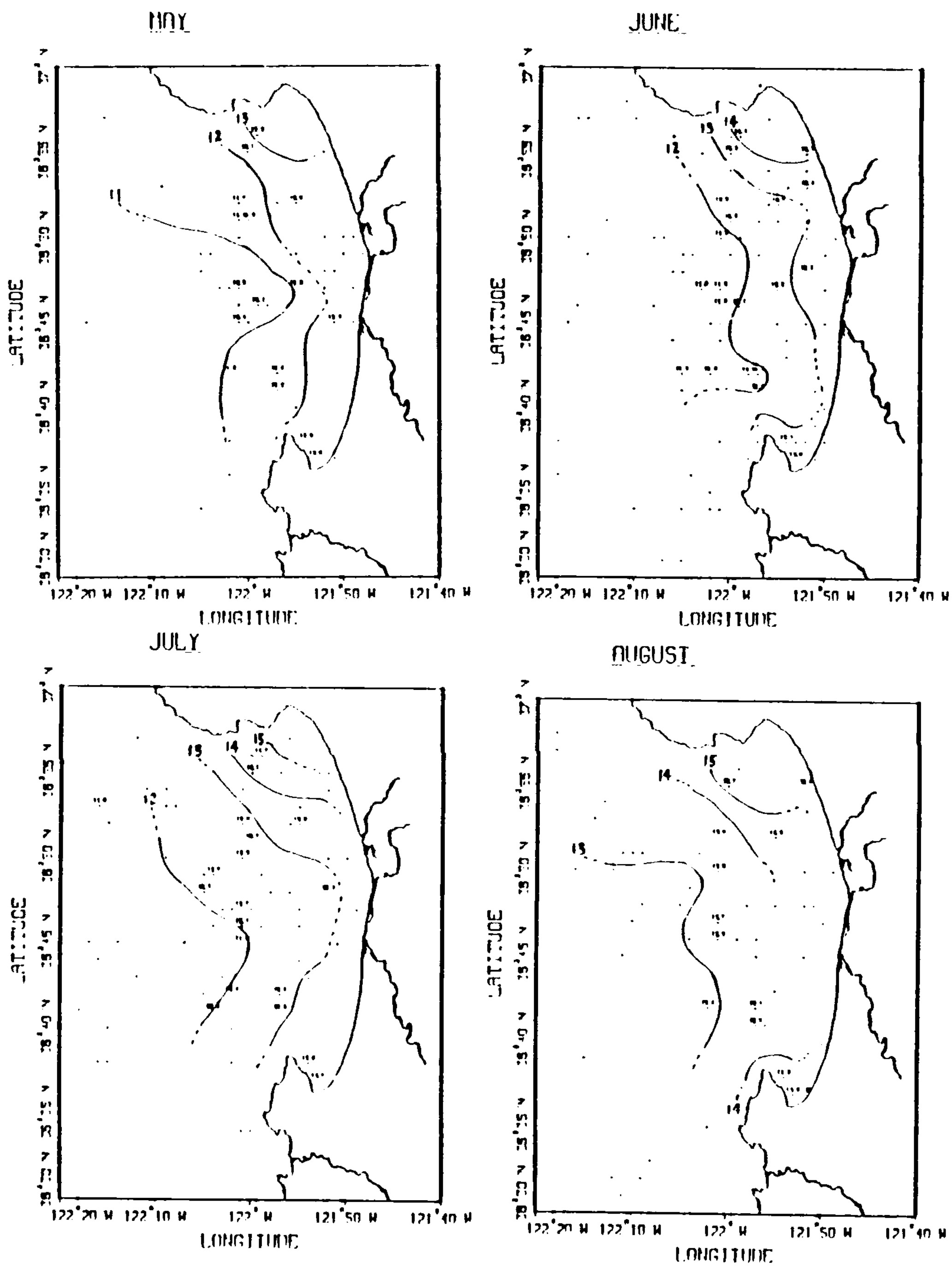

Figure 14 DISTRIBUTION OF THE MEAN MONTHLY SEA SURFACE TEMPERATURE FOR MAY THROUGH AUGUST

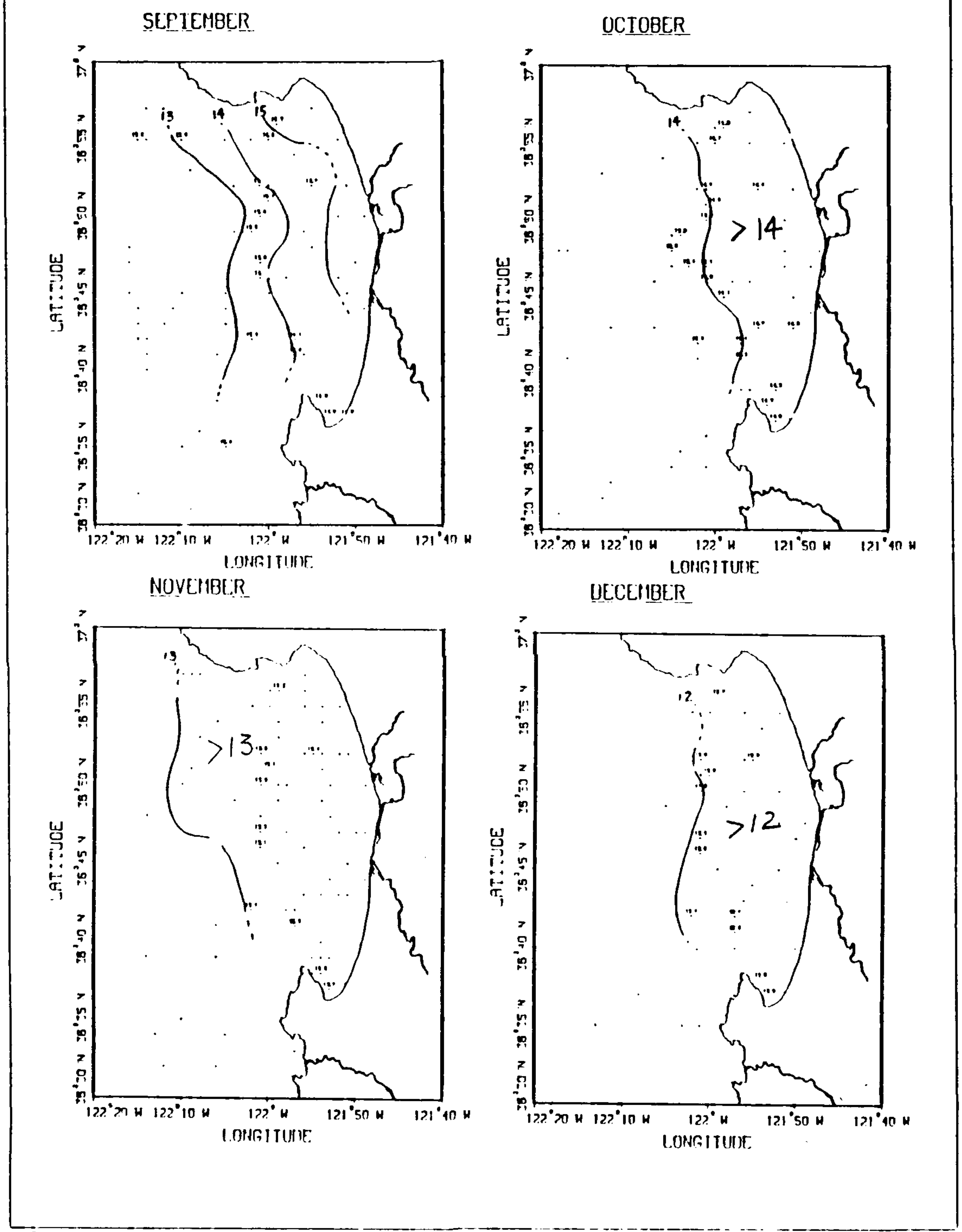

Figure 15 DISTRIBUTION OF THE MEAN MONTHLY SEA SURFACE TEMPERATURE FOR SEPTEMBER THROUGH DECEMBER

The mean sea surface temperature in the northern and southern areas of the Bay were consistently warmer than those in the center area for all months except November through February (when generally uniform temperatures prevail). The northern area exhibited consistently higher temperatures than the southern area throughout this period. The warm spot in the northern region is probably due to shallow water depths there which permit greater warming by solar insolation. Also, the shallower northern region is somewhat isolated from the effects of upwelling and thus does not undergo mixing with the deeper and colder waters.

3. Sea Surface Salinity In Monterey Bay

The distributions of the mean monthly sea surface salinity in Monterey Bay for January through December are shown at the end of this thesis in Figures 24-35. These figures show all hydrographic stations from collected data in every month (1989-1991 not included). Due to very sparse sampling (many 1 minute squares had only one profile), the contour lines were not plotted in these figures; but the figures show that low salinity occurred from January to March. Low salinity was observed in March (Fig. 26) when offshore salinity was lower than onshore. Surface salinities gradually increased during upwelling season and reached their maximun in June, and then slowly decreased through the year (Fig. 31-35).

C. MONTHLY MEAN TIME SERIES TEMPERATURE AND SALINITY

1. Data Distribution

Time series data in Monterey Bay were computed in the small area near the mouth of the Submarine Canyon (Fig. 1) as earlier mentioned (Chapter I.). Every hydrographic observation in that Canyon area (after 1951) was processed to get a representative monthly mean profile. Tables 3-4 showed the temporal distributions of temperature profiles at the sea surface and 50 m depth respectively.

Tables 3-4 show that data distribution over last four decades was sporadic with many gaps in coverage through the whole time series. There were no or few data between 1979 through 1988 and few data before 1954. The final time series contains 1546 hydrographic profiles taken in the 41-year period from 1951 to 1991 and provides possible viewing of time series fluctuations.

Similarly, Tables 5-6 show the temporal distributions of salinity over sea surface and at 50 m depth respectively. Table 5 indicates that there were only one half as many salinity as temperature profiles over last four decades. Table 6 shows that the number of salinity observations decreases rapidly with increasing depth. Many stations had temperature data only and few salinity data were taken at depths of 50 m or greater before 1968.

All the data were merged to form monthly mean time series. Figures 16-17 shows the entire time series of monthly mean temperature and salinity from 1951 to 1991. Only shallow

Table IV DISTRIBUTION BY YEAR AND MONTH OF SEA SURFACE TEMPERATURE OBSERVATIONS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SUM
1951	0	0	0	0	0	0	0	0	7	0	0	0	7
1952	0	0	0	1	1	1	0	1	7	0	1	0	12
1953	0	0	0	1	0	0	0	0	1	0	0	0	2
1954	0	0	4	5	4	4	5	5	8	3	3	2	43
1955	9	8	3	7	3	6	11	8	6	9	8	4	82
1956	6	5	11	5	7	6	7	8	6	4	9	8	82
1957	2	4	4	4	2	3	3	2	3	3	3	2	35
1958	2	0	0	3	2	0	4	2	1	4	3	4	25
1959	3	2	3	3	3	1	4	2	3	5	5	3	37
1960	3	3	3	3	4	4	2	4	4	4	3	3	40
1961	4	3	3	3	4	2	4	3	2	5	3	2	38
1962	5	2	4	3	2	4	4	4	3	3	2	3	39
1963	2	3	3	3	4	3	5	3	4	6	6	8	50
1964	7	4	6	7	7	9	8	3	6	7	5	5	74
1965	9	8	6	6	6	6	9	6	6	4	5	4	75
1966	6	5	4	8	6	7	8	8	6	7	9	7	81
1967	7	5	4	4	7	4	3	3	2	2	4	2	47
1968	4	3	1	3	4	2	4	2	2	3	2	1	31
1969	0	6	2	0	2	1	2	2	1	5	0	3	24
1970	1	3	7	10	8	11	15	2	2	4	5	1	69
1971	4	5	3	5	5	6	4	1	2	4	6	2	47
1972	5	3	4	5	5	5	3	2	3	5	4	2	46
1973	5	2	3	2	5	3	1	2	2	2	2	1	30
1974	2	2	3	2	0	0	3	3	2	2	1	3	23
1975	6	4	2	4	2	4	2	4	4	3	4	3	42
1976	4	2	4	2	4	2	2	4	2	2	2	2	32
1977	1	1	1	1	1	1	4	1	1	1	1	1	15
1978	2	1	2	2	2	1	1	1	0	0	0	0	12
1979	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	2	2	0	0	0	0	0	4
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	1	3	0	1	1	0	2	0	0	2	0	0	10
1985	0	1	0	0	0	0	0	0	0	0	0	0	1
1986	0	0	0	0	0	1	1	0	0	1	0	0	3
1987	0	0	1	0	0	1	0	0	0	2	0	0	4
1988	0	1	1	1	0	0	0	1	1	0	1	0	6
1989	0	1	1	5	1	3	4	12	29	31	32	32	151
1990	11	1	12	32	35	35	32	32	30	5	0	1	226
1991	0	1	0	0	0	0	0	0	0	0	0	0	1
SUM-	111	92	105	141	137	138	159	131	156	138	129	109	1546

Table V DISTRIBUTION BY YEAR AND MONTH OF 50 M TEMPERATURE OBSERVATIONS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SUM
1951	0	0	0	0	0	0	0	0	7	0	0	0	7
1952	0	0	0	0	0	0	0	0	7	0	1	0	8
1953	0	0	0	1	0	0	0	0	1	0	0	0	2
1954	0	0	1	1	1	1	0	3	8	3	3	2	23
1955	9	4	3	7	3	5	11	8	6	9	8	4	77
1956	6	5	11	5	7	6	6	6	6	3	8	8	77
1957	2	4	4	4	1	3	3	2	3	3	3	2	34
1958	2	0	0	3	2	0	4	1	1	3	3	4	23
1959	2	2	3	3	3	1	4	2	3	5	5	3	36
1960	3	3	3	3	4	4	2	4	4	4	3	3	40
1961	3	3	3	3	4	2	3	3	2	5	3	2	36
1962	5	2	4	3	2	4	4	3	3	3	2	3	38
1963	2	3	3	3	4	3	5	3	4	6	6	7	49
1964	7	4	6	7	7	7	8	3	6	7	5	5	72
1965	9	7	6	5	6	6	9	6	6	3	4	4	71
1966	5	4	3	8	5	7	7	6	5	4	5	4	63
1967	6	3	2	2	4	2	3	3	2	2	4	2	35
1968	4	3	1	3	4	2	4	2	2	3	2	1	31
1969	0	6	2	0	2	1	2	2	1	5	0	3	24
1970	1	3	7	10	8	11	15	2	2	4	3	1	67
1971	3	5	3	5	5	6	4	1	2	4	6	2	46
1972	5	3	4	5	5	5	3	2	3	5	4	2	46
1973	5	2	3	2	5	3	1	2	2	2	2	1	30
1974	2	2	3	2	0	0	3	3	2	2	1	3	23
1975	4	3	1	2	1	2	1	2	2	2	2	2	24
1976	2	1	2	1	2	1	1	3	1	1	1	1	17
1977	1	1	1	1	1	1	4	1	1	1	1	1	15
1978	2	1	2	2	2	1	1	1	0	0	0	0	12
1979	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	2	2	0	0	0	0	0	4
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	1	3	0	1	1	0	2	0	0	2	0	0	10
1985	0	1	0	0	0	0	0	0	0	0	0	0	1
1986	0	0	0	0	0	1	1	0	0	1	0	0	3
1987	0	0	1	0	0	1	0	0	0	2	0	0	4
1988	0	1	1	1	0	0	0	1	1	0	1	0	6
1989	0	1	1	5	1	3	4	12	29	31	32	32	151
1990	11	1	12	32	35	35	32	32	30	5	0	1	226
1991	0	1	0	0	0	0	0	0	0	0	0	0	1
SUM=	102	82	96	130	125	126	149	119	152	130	118	103	1432

Table VI DISTRIBUTION BY YEAR AND MONTH OF SEA SURFACE SALINITY OBSERVATIONS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SUM
1951	0	0	0	0	0	0	0	0	0	0	0	0	0
1952	0	0	0	1	1	1	0	1	1	0	1	0	6
1953	0	0	0	1	0	0	0	0	0	0	0	0	1
1954	0	0	2	2	2	4	5	5	4	3	3	2	32
1955	5	3	1	3	0	5	5	4	0	5	3	0	34
1956	3	3	6	2	3	3	3	4	3	2	4	4	40
1957	2	4	3	3	1	2	2	2	3	1	3	2	28
1958	2	0	0	1	2	0	3	1	1	4	3	4	21
1959	3	2	3	3	3	1	4	2	3	3	4	3	34
1960	3	3	3	3	4	4	2	4	4	4	3	3	40
1961	4	3	3	3	4	2	4	3	2	3	2	2	35
1962	4	2	3	3	2	4	4	3	2	3	2	3	35
1963	2	3	3	3	4	2	5	3	4	3	3	4	39
1964	2	2	3	3	3	4	4	1	2	3	3	2	32
1965	1	4	3	3	3	3	5	2	1	2	2	2	31
1966	2	3	3	3	3	3	4	4	3	2	4	3	37
1967	4	0	2	1	1	0	1	1	1	2	4	2	19
1968	4	3	0	3	4	2	4	1	0	2	2	1	26
1969	0	2	0	0	1	1	2	2	0	4	0	3	15
1970	1	2	6	3	2	3	5	2	2	4	5	1	36
1971	4	5	3	5	5	5	4	1	2	3	6	2	45
1972	5	3	4	5	4	3	3	2	3	3	3	2	40
1973	1	2	3	2	3	3	1	2	2	2	2	1	24
1974	0	0	0	0	0	0	1	3	2	2	1	2	11
1975	6	4	2	4	2	4	2	4	4	3	4	3	42
1976	4	2	4	2	4	2	2	2	2	2	2	2	30
1977	1	1	1	1	1	1	0	1	1	1	1	1	11
1978	2	1	2	2	2	1	1	1	0	0	0	0	12
1979	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	2	2	0	0	0	0	0	4
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	1	3	0	1	1	0	2	0	0	2	0	0	10
1985	0	1	0	0	0	0	0	0	0	0	0	0	1
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	1	0	0	0	1	1	0	1	0	4
1989	0	1	1	5	1	3	4	3	3	1	2	2	26
1990	5	1	2	2	4	5	2	2	0	1	0	1	25
1991	0	1	0	0	0	0	0	0	0	0	0	0	1
SUM=	71	64	66	74	70	73	86	67	56	70	73	57	827

Table VII DISTRIBUTION BY YEAR AND MONTH OF 50 M SALINITY OBSERVATIONS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	SUM
1951	0	0	0	0	0	0	0	0	0	0	0	0	0
1952	0	0	0	0	0	0	0	0	1	0	1	0	2
1953	0	0	0	1	0	0	0	0	0	0	0	0	1
1954	0	0	0	1	0	1	0	1	0	0	0	0	3
1955	0	0	0	0	0	0	0	0	0	1	0	0	1
1956	0	0	0	0	0	0	0	0	0	0	0	0	0
1957	0	0	0	0	0	0	0	0	0	0	0	0	0
1958	0	0	0	0	0	0	0	0	0	0	0	0	0
1959	0	0	0	0	0	0	0	0	0	0	0	0	0
1960	0	0	0	0	0	0	0	0	1	0	0	0	1
1961	0	0	0	1	0	0	0	0	0	1	0	0	2
1962	1	0	0	0	0	0	0	0	0	0	0	0	1
1963	0	0	0	0	0	0	0	0	0	0	0	0	0
1964	0	0	0	0	0	0	0	0	0	0	0	0	0
1965	1	0	0	0	0	0	1	0	0	0	0	0	2
1966	0	0	0	0	0	0	0	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	2	2	4	1	0	2	2	1	14
1969	0	2	0	0	1	1	2	2	0	4	0	3	15
1970	1	2	6	3	2	3	5	2	2	4	3	1	34
1971	3	5	3	5	5	5	4	1	2	3	6	2	44
1972	5	3	4	5	4	3	3	2	3	3	3	2	40
1973	1	2	3	2	3	3	1	2	2	2	2	1	24
1974	0	0	0	0	0	0	1	3	2	2	1	2	11
1975	4	3	1	2	1	2	1	2	2	2	2	2	24
1976	2	1	2	1	2	1	1	1	1	1	1	1	15
1977	1	1	1	1	1	1	0	1	1	1	1	1	11
1978	2	1	2	2	2	1	1	1	0	0	0	0	12
1979	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	2	2	0	0	0	0	0	4
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	1	3	0	1	1	0	2	0	0	2	0	0	10
1985	0	1	0	0	0	0	0	0	0	0	0	0	1
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	1	0	0	0	1	1	0	1	0	4
1989	0	1	1	5	1	3	4	3	3	1	2	2	26
1990	5	1	2	2	4	5	2	2	0	1	0	1	25
1991	0	1	0	0	0	0	0	0	0	0	0	0	1
SUM=	27	27	25	33	29	33	34	25	21	30	25	19	328

(less than 50 m) sampling occurred from 1951 to 1968 and few or no observations were available from 1979 to 1988. Good time series coverage of deep profiles occurred from 1968 to 1978 and from 1989 to 1990.

2. The Monthly Mean Time Series Of Temperature And Salinity In Monterey Bay

Figure 18 shows the time series of mean temperature during the period 1954 to 1968 over sea surface and 50 m depth when good coverage was available. Dotted lines indicate the annual mean cycle at the sea surface and 50 m depth. Anomalous temperatures of more than 1°C higher than normal were found in 1957, 1959 and 1963, and even greater anomalies in 1958, 1965 and 1967. All these anomalous values occurred

in September in the Oceanic Period. The 50 m depth temperature was 0.5°-1°C higher than normal in these years, but the anomaly did not start until December (except during 1967), three months later than at the surface. In almost every case, all high temperature water returned to normal nearly simultaneously in March.

Figure 19 showed a deeper water time series from 1968 to 1978 in Monterey Bay. The average seasonal pattern of varying oceanographic conditions is strongly modified in certain months by changes in the vertical thermal structure (Fig. 19). The 7°-10°C isotherms were as much as 80 m deeper than their mean depths in August to September of 1968, 1969 and 1972, and 20-50 m deeper September to December of 1976 and 1977. The average depth of of the 8°C isotherm lies at depths of 250 and 300 m from July to February, but the 8°C isotherm was at depths of 350 m from August to September 1968, of 340-380 m from August to October 1969 and of 370 m in August 1972. The 9°C and 10°C isotherms were about 50 m deeper than normal in 1969 and 1972 (except 1968 return normal), but the anomalous deepenings of these isotherms did not start until October, two months later than of the 8°C isotherm. The three isotherms were also deeper than normal from September to February of 1976-77 and 1977-78, although not as markedly so as in 1969-70 and 1972-73. Again in these winters, anomalous deepening of the 9°C and 10°C isotherms lagged that of the 8°C

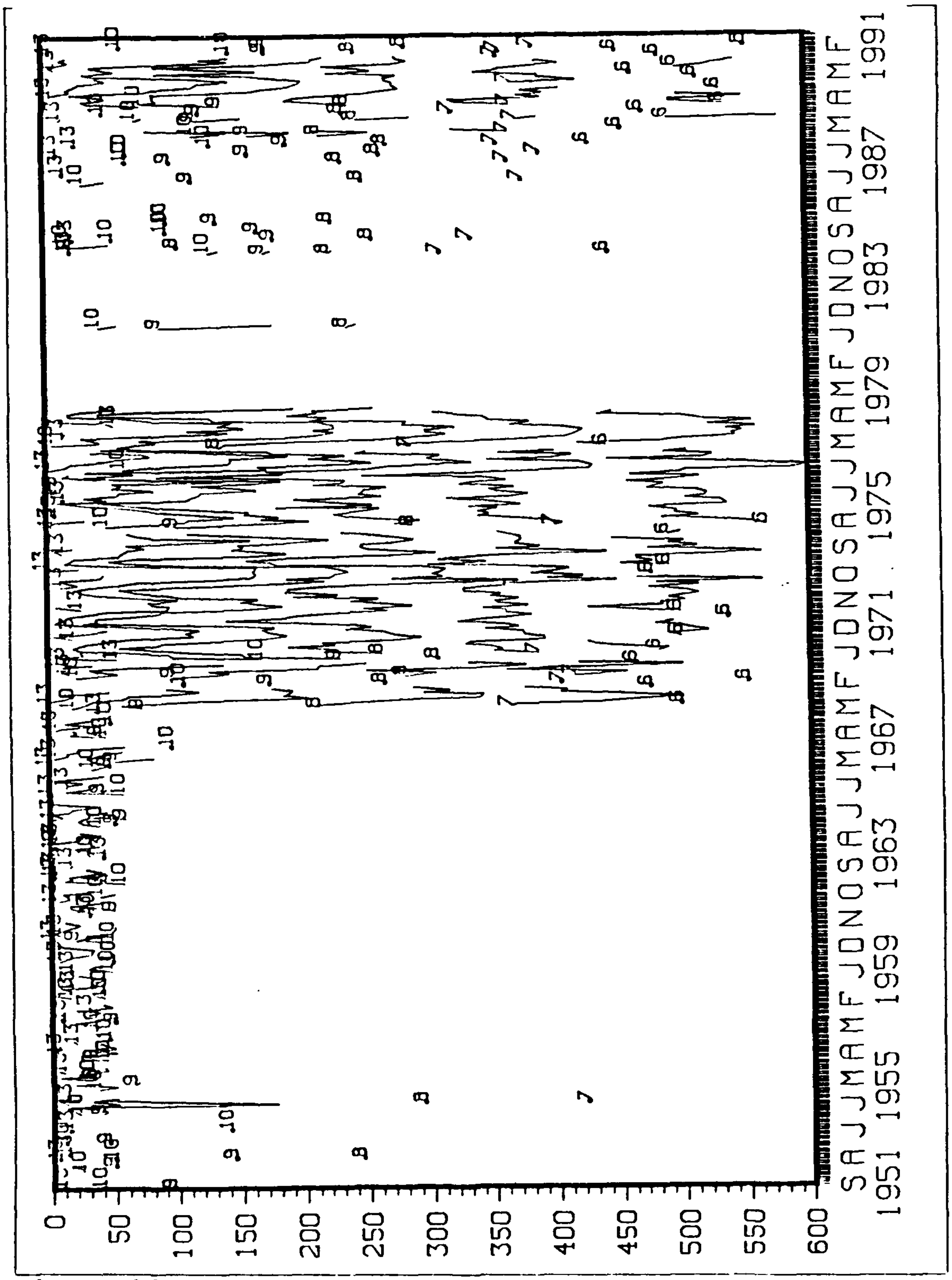

Figure 16 TIME SERIES VERTICAL SECTION OF TEMPERATURE (1951-1991)

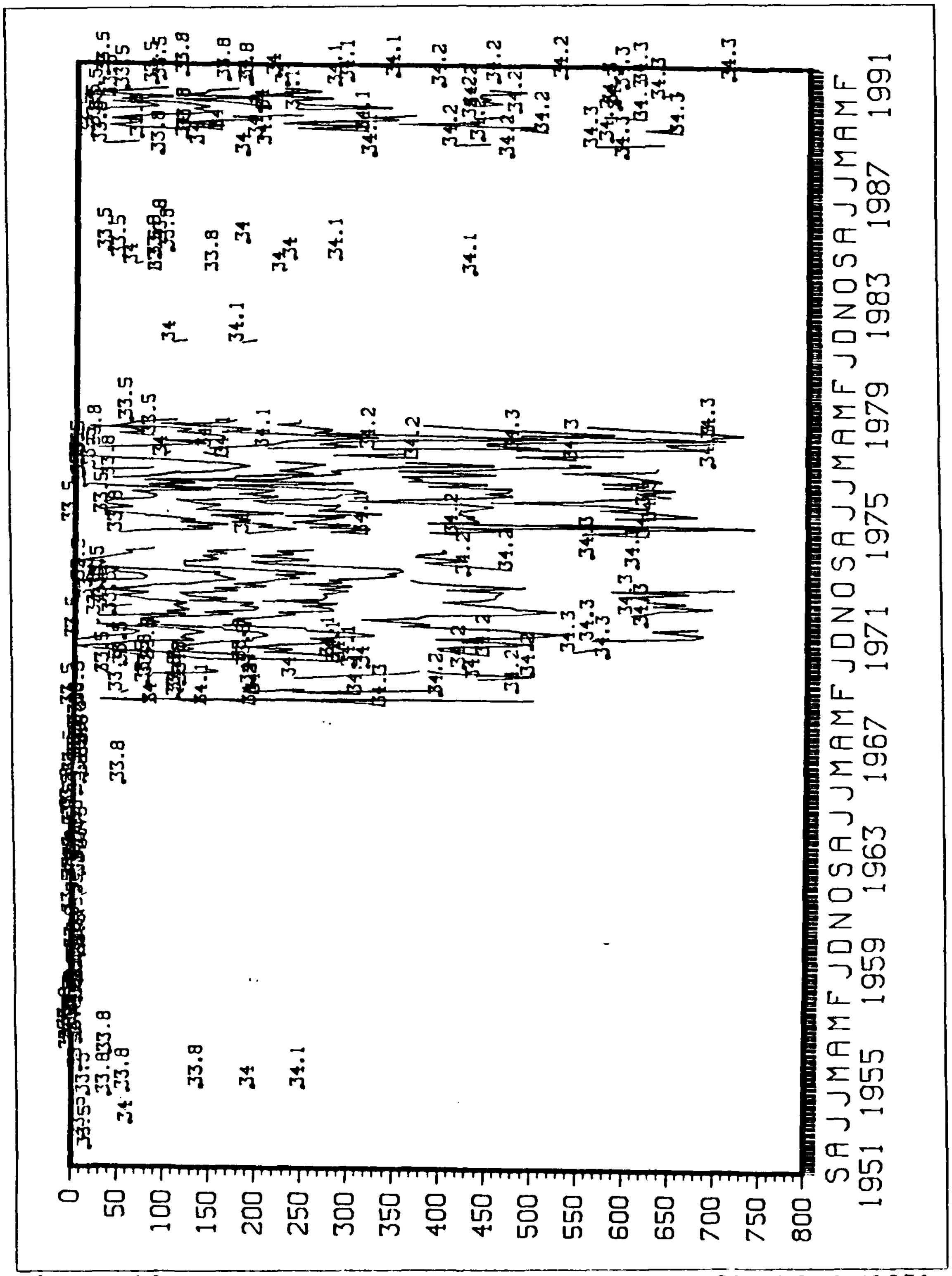

Figure 17 TIME SERIES VERTICAL SECTION OF SALINITY (1951-1991)

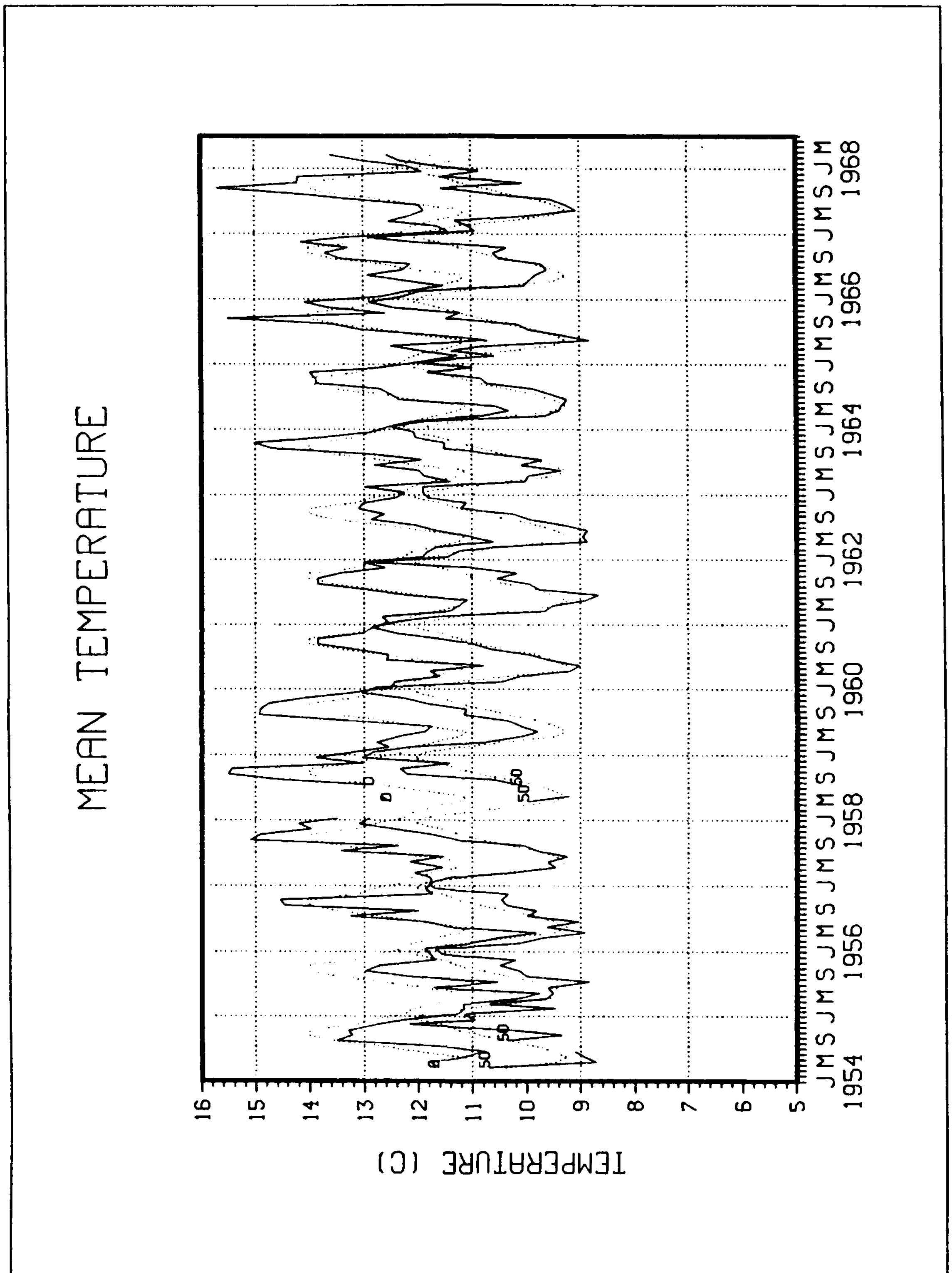

Figure 18 TIME SERIES OF SEA SURFACE AND 50 M TEMPERATURE (1954-1968)

isotherm. All three isotherms returned to normal depths nearly simultaneously after February. Isotherm depths were near normal in the winters of 1970-71, 1971-72 and 1974-75, and were consistently shallower than normal in the winter of 1975-76. The 9°C and 10°C isotherms were shallower than normal in March 1971 and 1976; but 8°C isotherm was shallower than normal in April 1971 and 1976, one month later than that of the 9°C and 10°C isotherms.

Time series of monthly mean salinity has generally similar interannual variations (Fig. 20) as temperature. Depressions of the 34 ppt isohaline by 50-100 m or more occurred in August 1968, May-December 1969, in the winter of 1972-73, 1976-77 and 1977-78. The 34 ppt isohaline was at near-normal depths in the winters of 1970-71, 1974-75, and 1975-76, and shallower than normal in winter 1973-74. The 34.2 and 34.3 ppt isohalines were abnormally deep in November 1974 (not showed in Fig. 19 at the same depths). Again isotherms shallower than normal occurred in the springs of 1971 and 1976.

Figure 21 shows salinity variations with time at different water levels. Very low surface salinity was observed in March (spring transition period) of 1970, 1975 and 1978 and late 1970; and also found in June of 1969 and August of 1971. Very low salinty was found in March probably as a result of onshore Ekman transport of low salinity from offshore. Saur

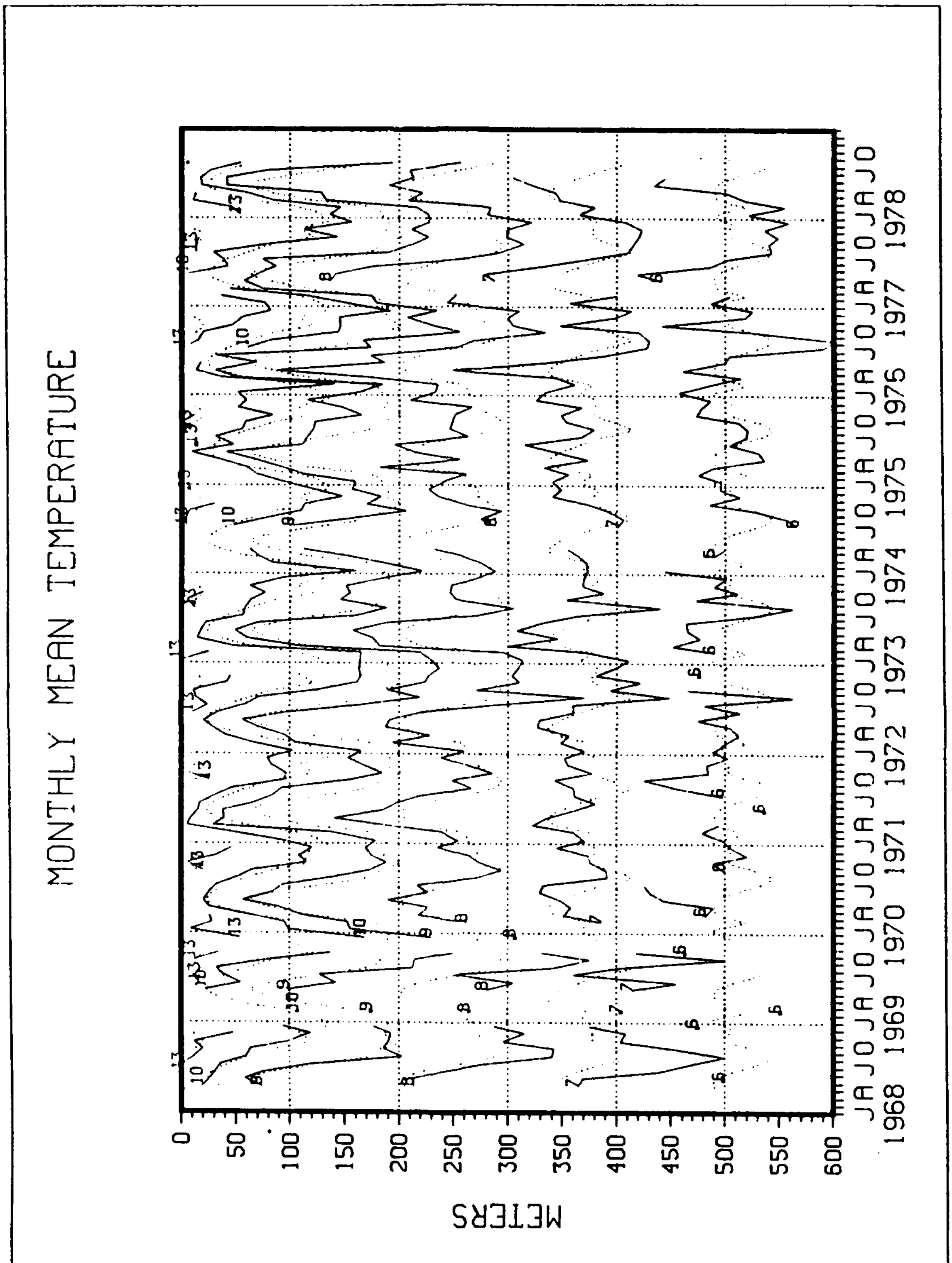

Figure 19 TIME SERIES VERTICAL SECTION OF TEMPERATURE (1968-1978)

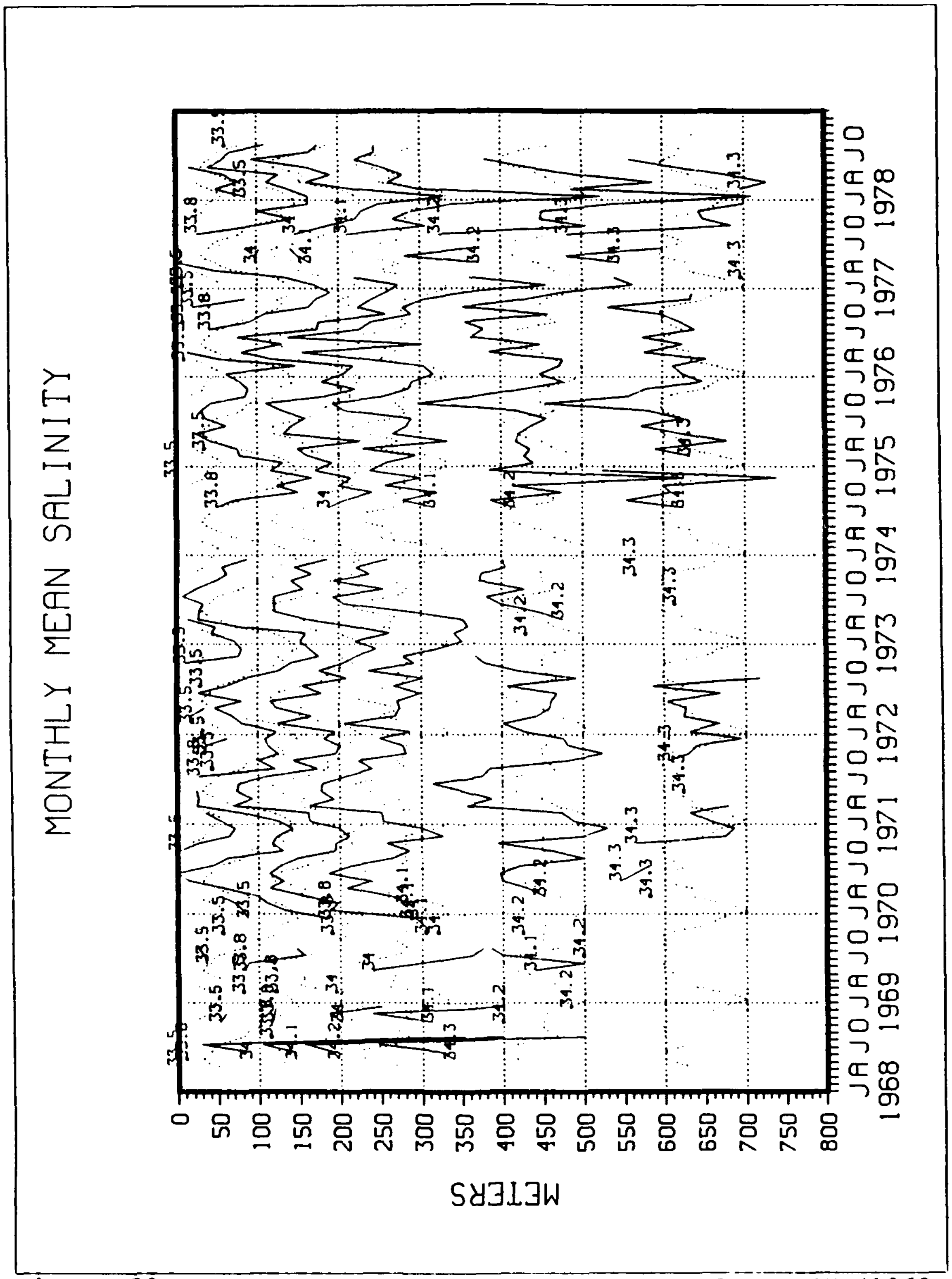

Figure 20 TIME SERIES VERTICAL SECTION OF SALINITY (1968-1978)

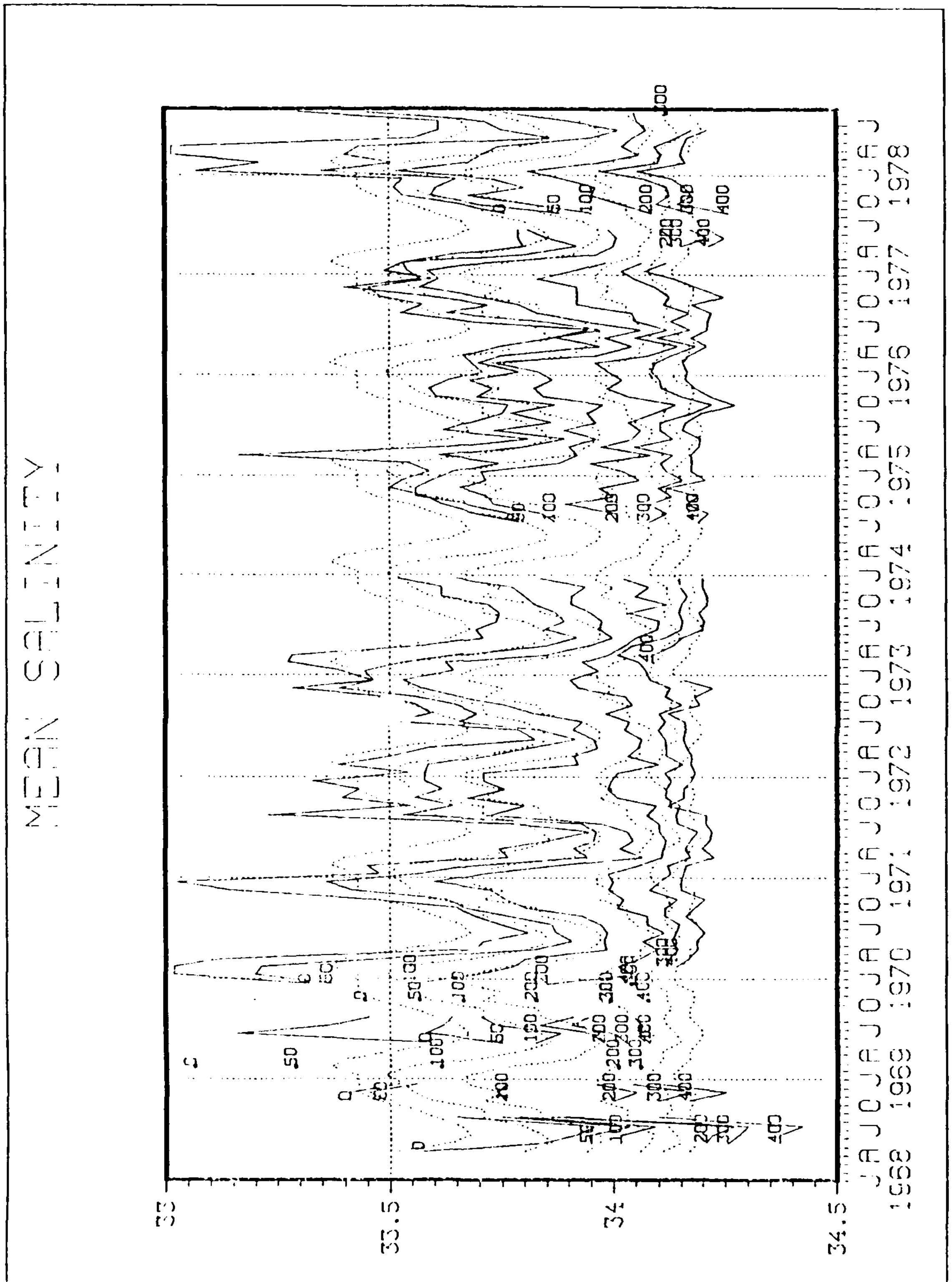

Figure 21 TIME SERIES OF SALINITY IN SELECTED LEVELS (1968-1978)

(1980) showed that, based on surface salinity observiations made by ships of opportunity between San Francisco and Honolulu during 1966-74, a core of low-salinity surface water occurs off San Francisco throughout the year and tends to more onshore in spring and offshore in Autumn; indeed, figure 26 in March showed low salinity from offshore.

Figure 22 shows the monthly mean temperature time series from 1988 to 1991, again with the mean annual cycles shown as dotted lines. The 7°-13°C isotherms were normal in 1989. The 8°-9°C isotherms were as much as 50-80 m deeper than their mean depths in April 1990 and returned to normal depths in June, and 80 m deeper in August of 10°C isotherm. Isotherms were shallower than normal shown in August, November 1988 and December 1990.

Figure 23 shows the time series of salinity. Again, there were about the same pattern of varying curves except the 34.1 PPT isohaline was deeper than normal during fall 1989 and shallower in early 1990.

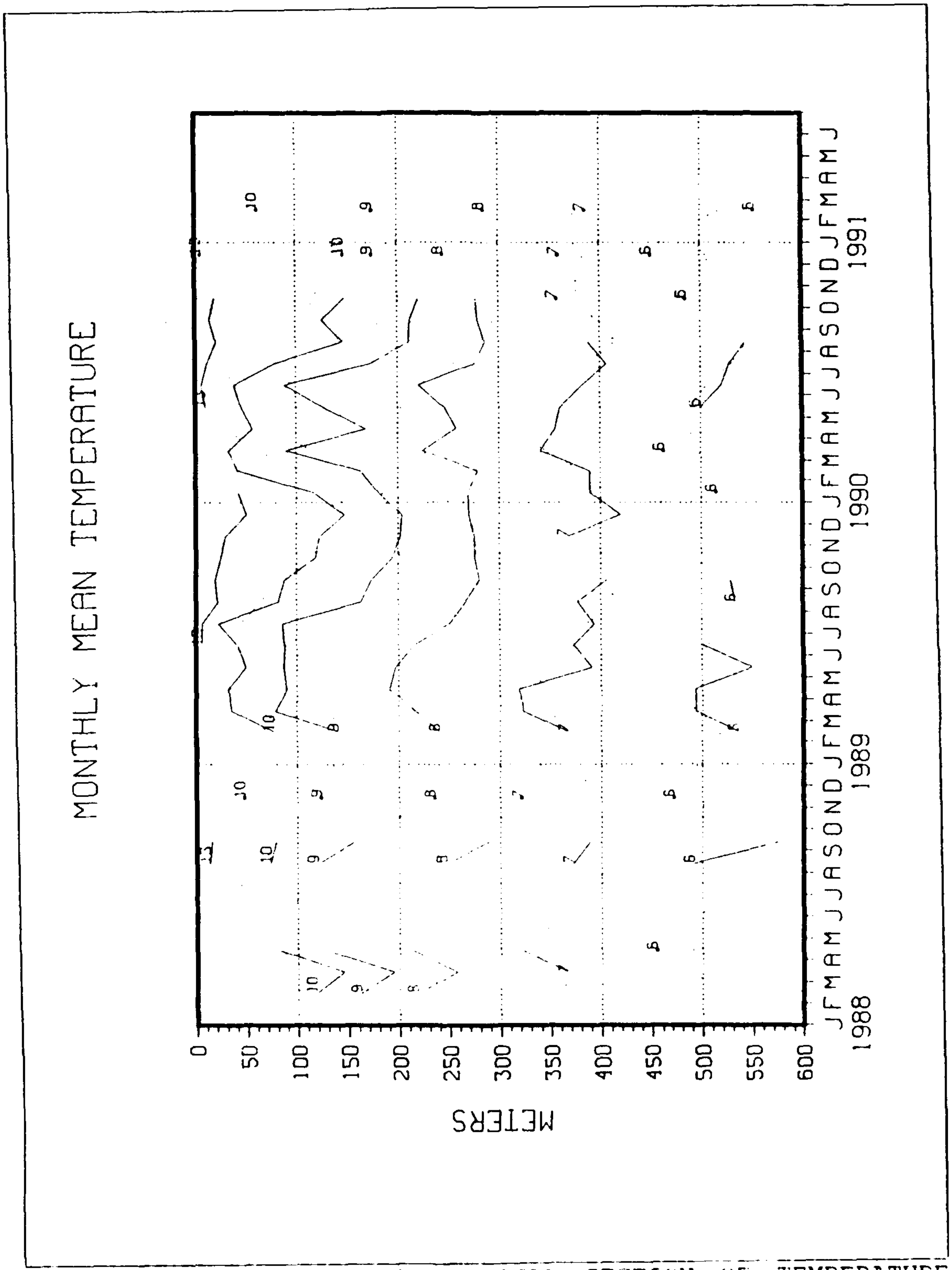

Figure 22 TIME SERIES VERTICAL SECTION OF TEMPERATURE (1988-1991)

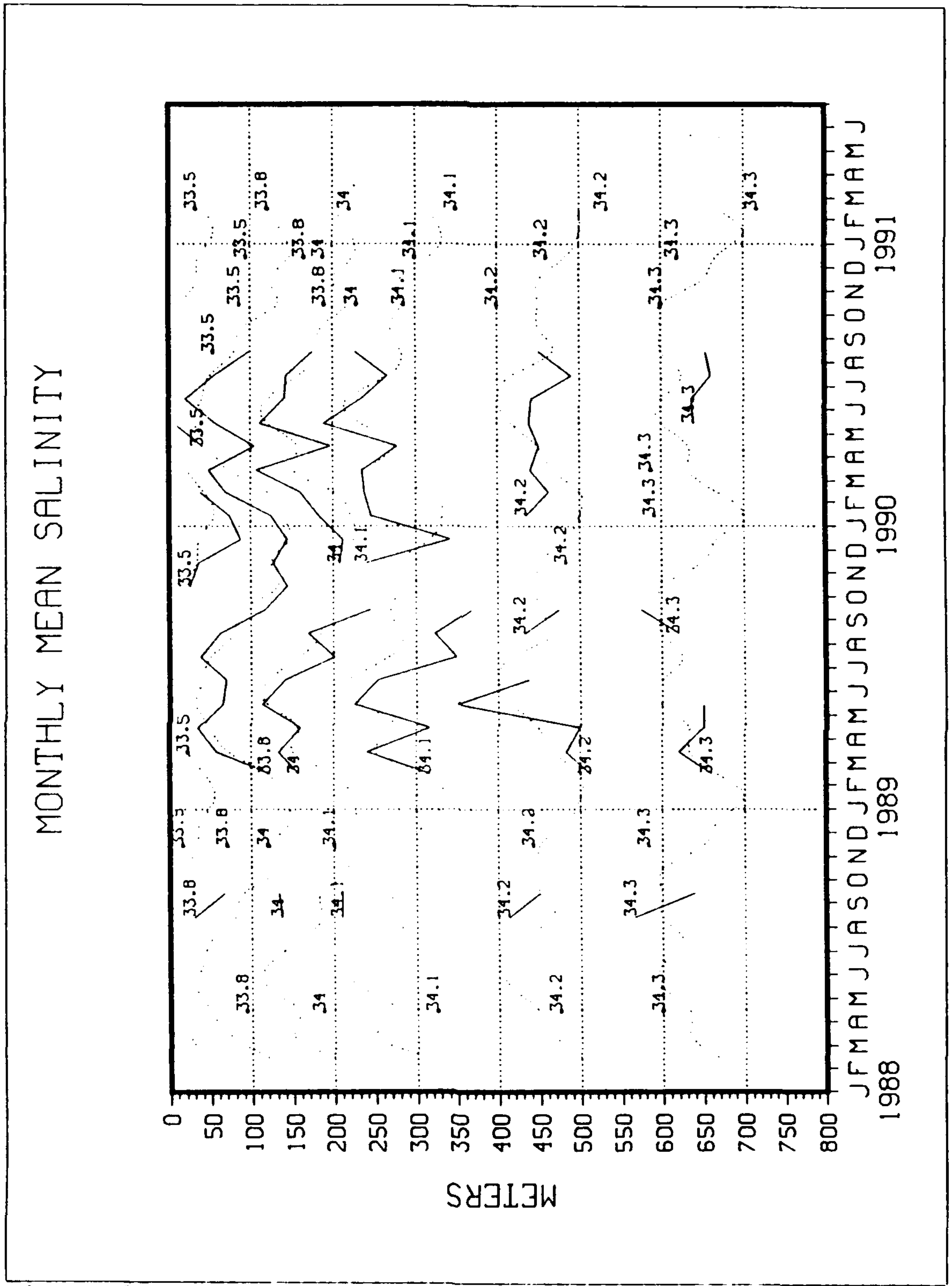

Figure 23 TIME SERIES VERTICAL SECTION OF SALINITY (1988-1991)

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

(1) Annual cycle of monthly regression T-S curves can be obtained by least-squares adjustment method. The results of regression T-S curves (Fig. 9) appeared "seasons" cycle in Monterey Bay. These seasons are the upwelling period from April to July; the oceanic period, from August to October; the Davidson Current period, from November to February; and the spring transition period in March. Regression equations of salinity on temperature can fill in salinity data if the profile has temperature data only.

(2) Low salinity was observed near the surface of Monterey Submarine Canyon from January to April, especially on March (Fig. 12). Low salinity water intruded into the Bay from offshore (Fig. 24-26). This agreed with Saur's (1980) observations that a core of low salinity surface water occurred off San Francisco and tended to move onshore in spring.

(3) The annual cycle of temperature (Fig. 10) showed similar "seasons" pattern with regression T-S curves (except on spring transition); it agreed with Lammers (1971)

observations. Hence, water mass analysis is believed to be major factor for separating "seasons" in Monterey Bay.

The annual cycle of salinity (Fig. 12) was similar with temperature one (Fig. 10) (except in deeper water). These variations in deep water may reflect mainly variations in the California Current and Undercurrent.

(4) All three plots, T-S, temperature and salinity (Fig. 9,10 and 12) agreed that the strongest rates of upwelling occurred during April through May.

Spatial distributions of sea surface temperature (Fig. 13-14 April-May) were also observed that low temperature water intruded into the center of the Bay. These observations may indicate that the strongest rates of upwelling occur in that period.

(5) The spatial distributions of sea surface temperature (Fig. 13-15) showed that March-April are the coldest months over the Bay. The northern and southern areas of the Bay were warmer than central area for all months except November through February (when uniform temperatures prevail over the Bay); the northern area exhibited higher temperature than southern area throughout this period.

(6) The time series of monthly isotherm depth in the mouth of the Canyon show different time periods: they are shallower in 1954-68 (Fig. 18), deeper in 1968-78 (Fig. 19) and 1988-91 (Fig. 22). Abnormal high surface temperatures occurred in September (oceanic period) of some years and may

be related to weather conditions. Anomalous high temperatures at 50 m depth occurred three months later than at the surface during the same year. This may indicate that anomalous onshore Ekman transport at that period. Both phenomena in the upper layer were caused by local forcing which was certainly associated with anomalous weather conditions.

The anomalous high temperature in deep water (see Fig. 19) occurred in years which had different pattern from the upper layer; the shallower isotherms (such as 9° or $10^{\circ}C$) always lag the deeper isotherms (such as 8° or $7^{\circ}C$). It may indicate that the interannual variations in deep water may not be caused by local forcing; remote forcing may exist in deep water.

McLain and Thomas (1983) suggested that remote forcing by poleward-propagating coastal trapped waves from tropics may depress the thermal structure along the coast in some years by 50-100 m.

B. RECOMMENDATIONS

The oceanographics data collected throughout Monterey Bay is insuffecent to characterize either temporal or spatial variability. For monitoring long-term ocean thermal structure, it is recommended that a complete data cycle be collected at least weekly intervals; and the series of stations should be expanded to give coverage offshore into the California Current area. As a result, relationships between

California Current, Undercurrent and local water type may be compared.

Data management will become more and more important in the future years. Development of an effective data base is required so that all oceanographic data collected in Monterey Bay over the years can be made available to all investigators desiring its use.

Future studies should be made of the monthly mean current pattern in the Bay which may be compared with the isotherm depths. Correlation studies of weather and other oceanographic stations along the coast of North America and their energy spectrum may be needed for detecting coastal trapped waves and large scale forcing.

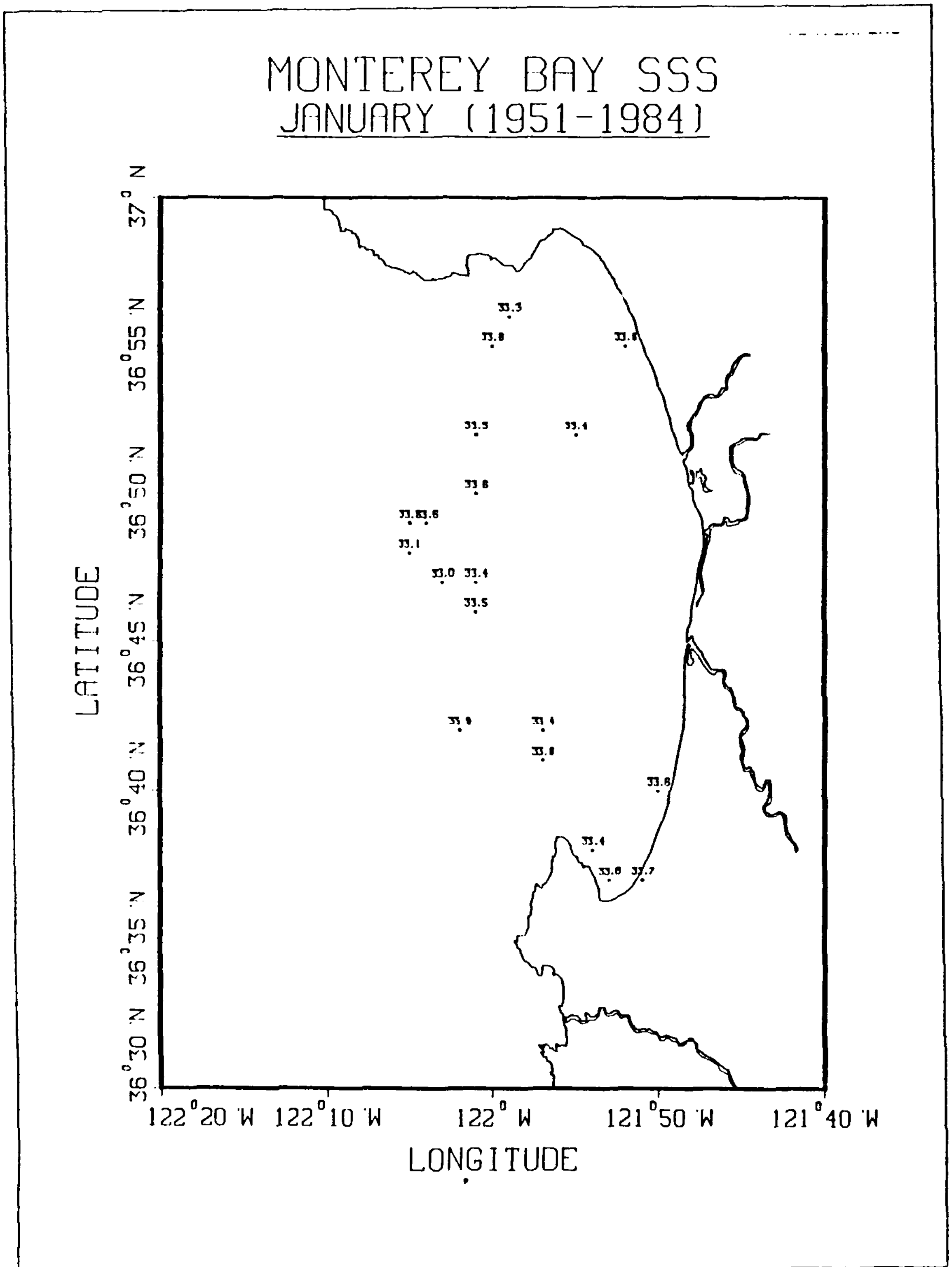

Figure 24 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (JANUARY)

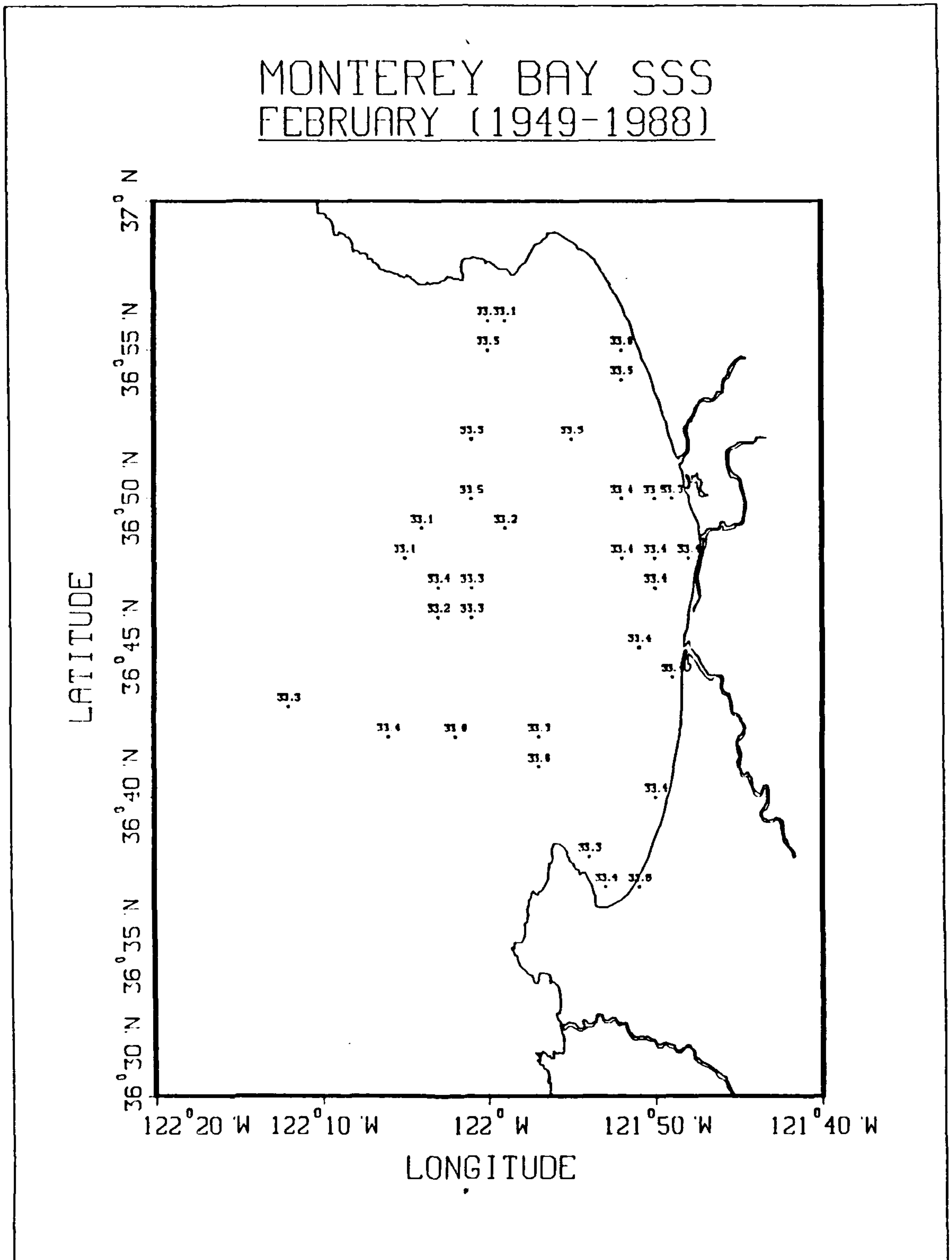

Figure 25 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (FEBRUARY)

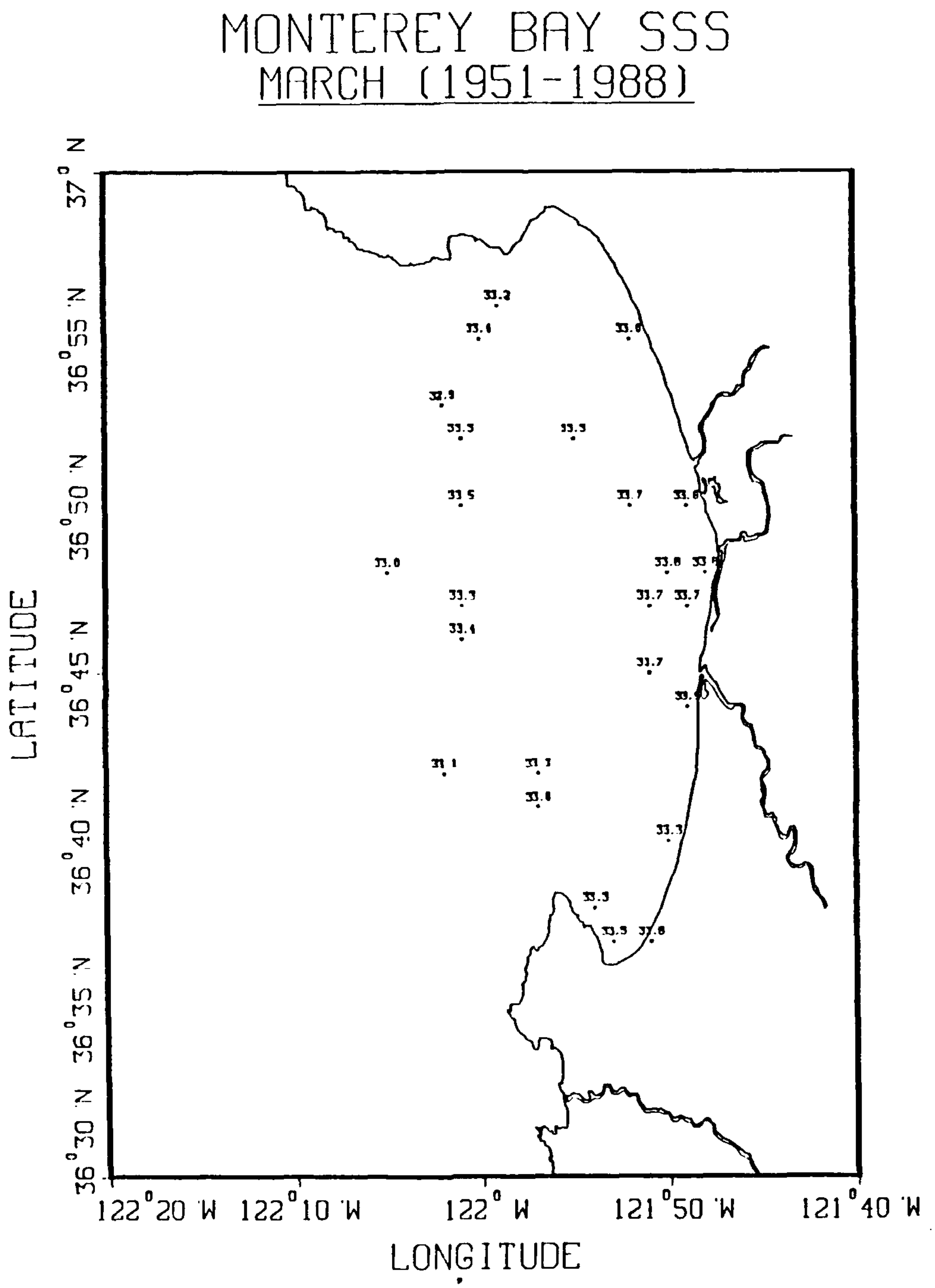

Figure 26 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (MARCH)

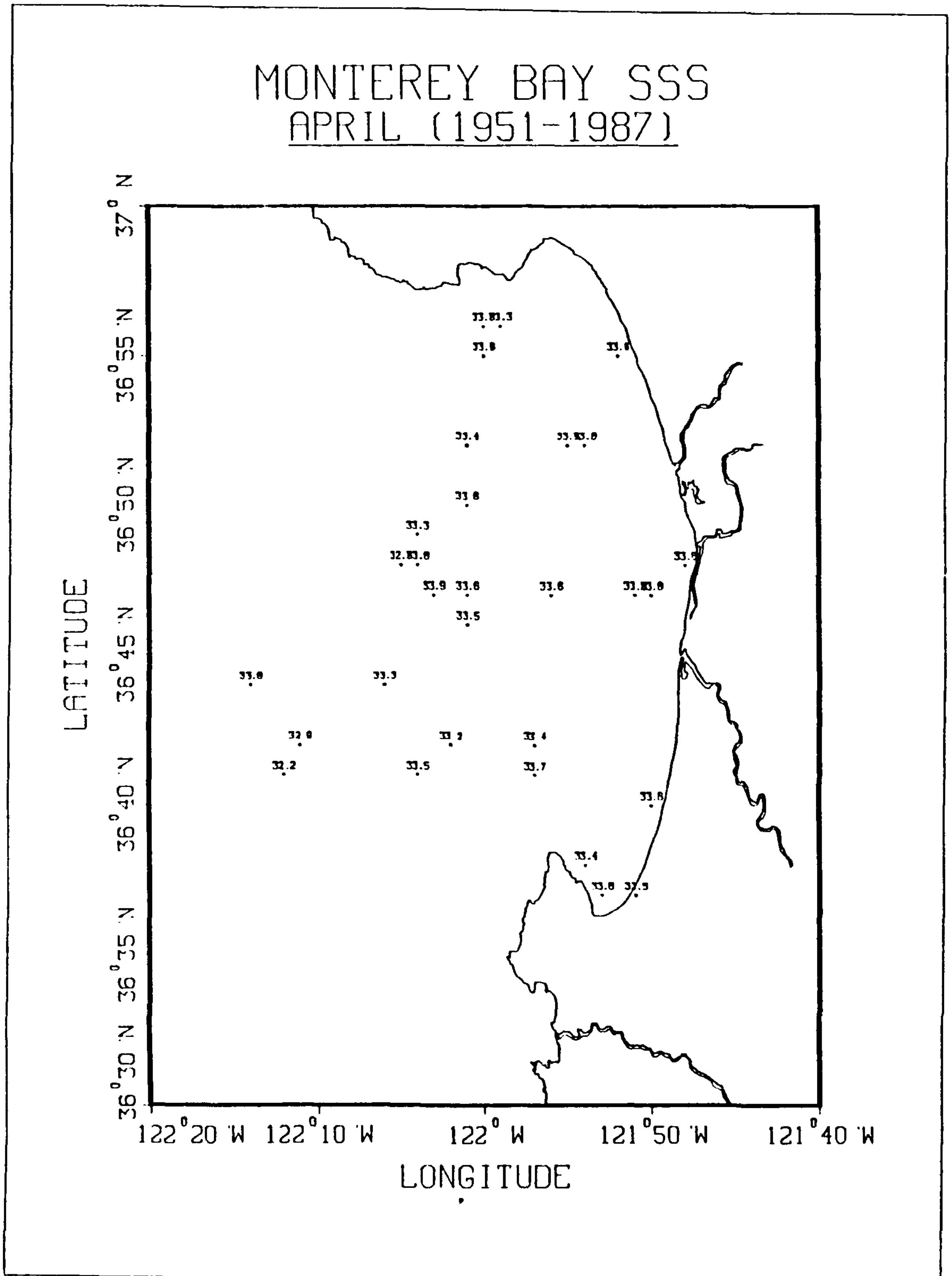

Figure 27 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (APRIL)

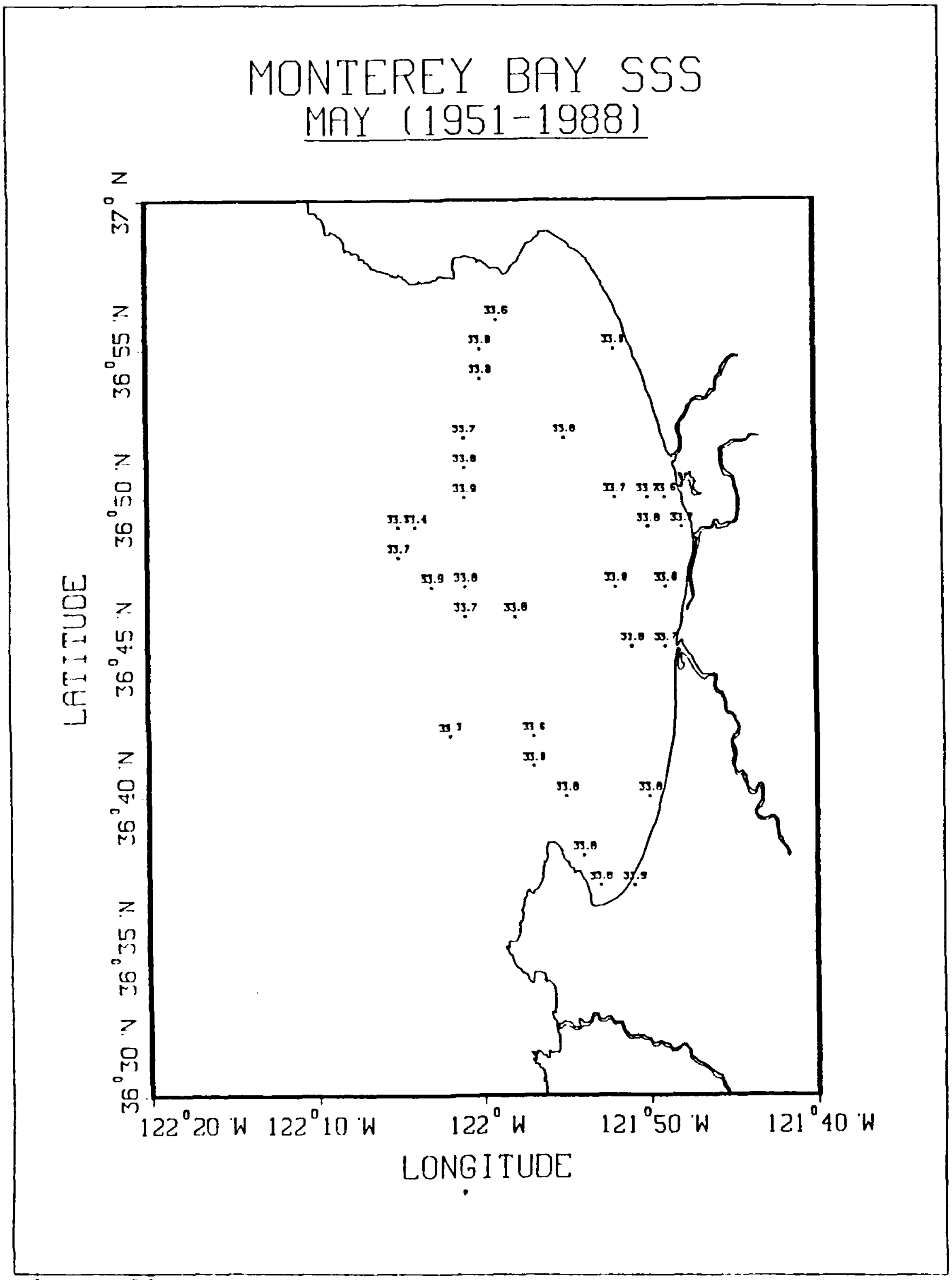

Figure 28 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (MAY)

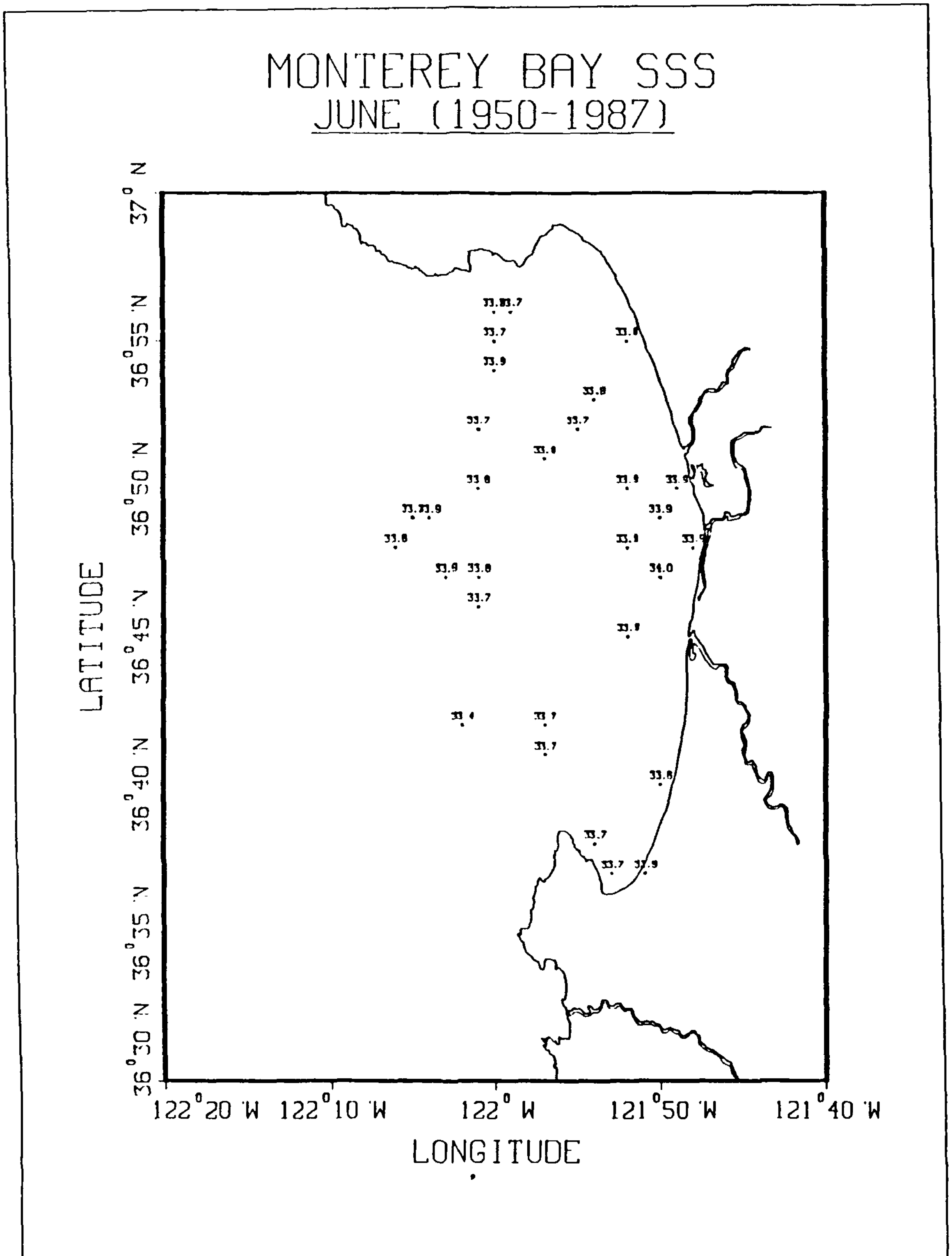

Figure 29 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (JUNE)

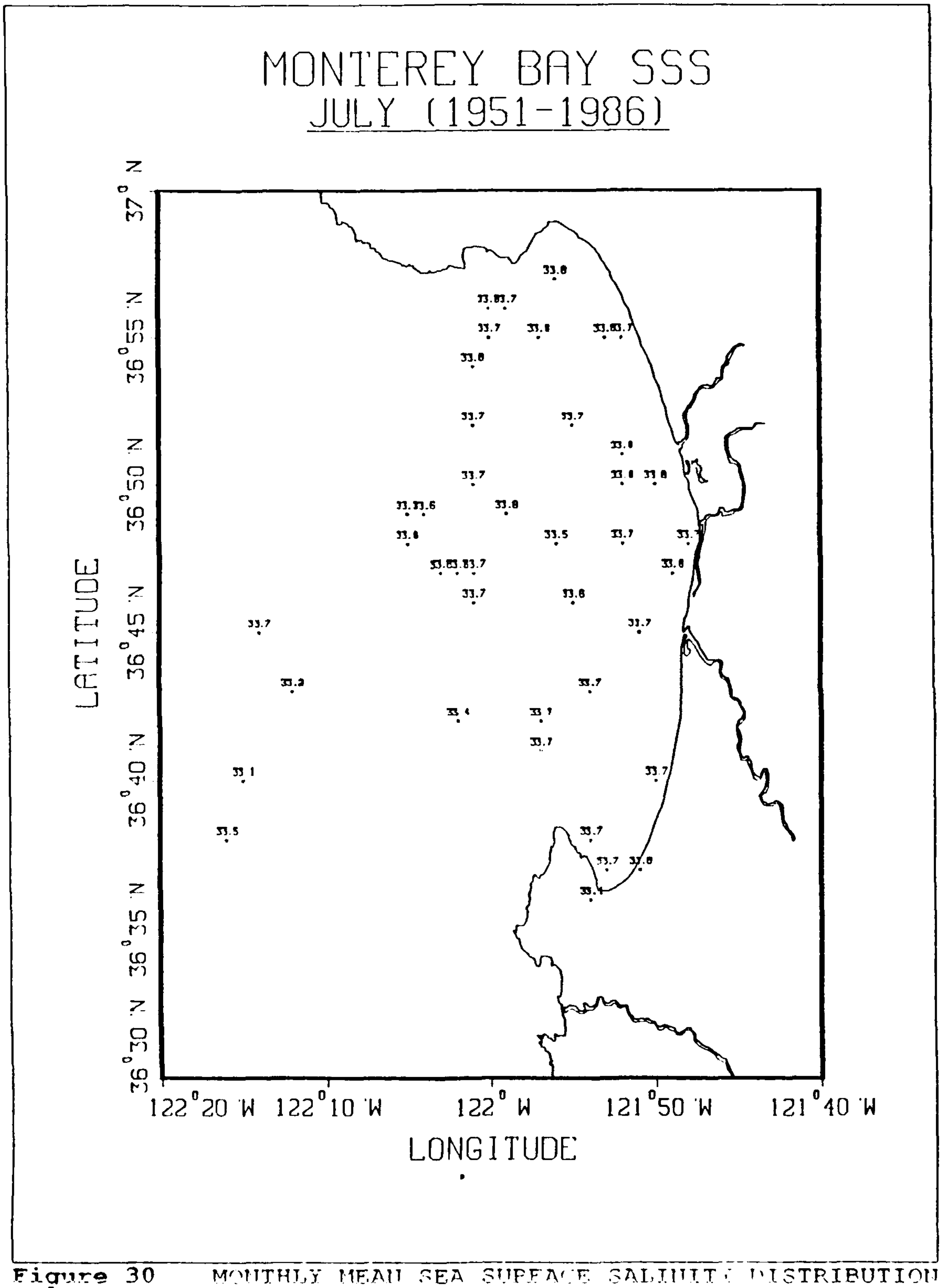

Figure 30 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (JULY)

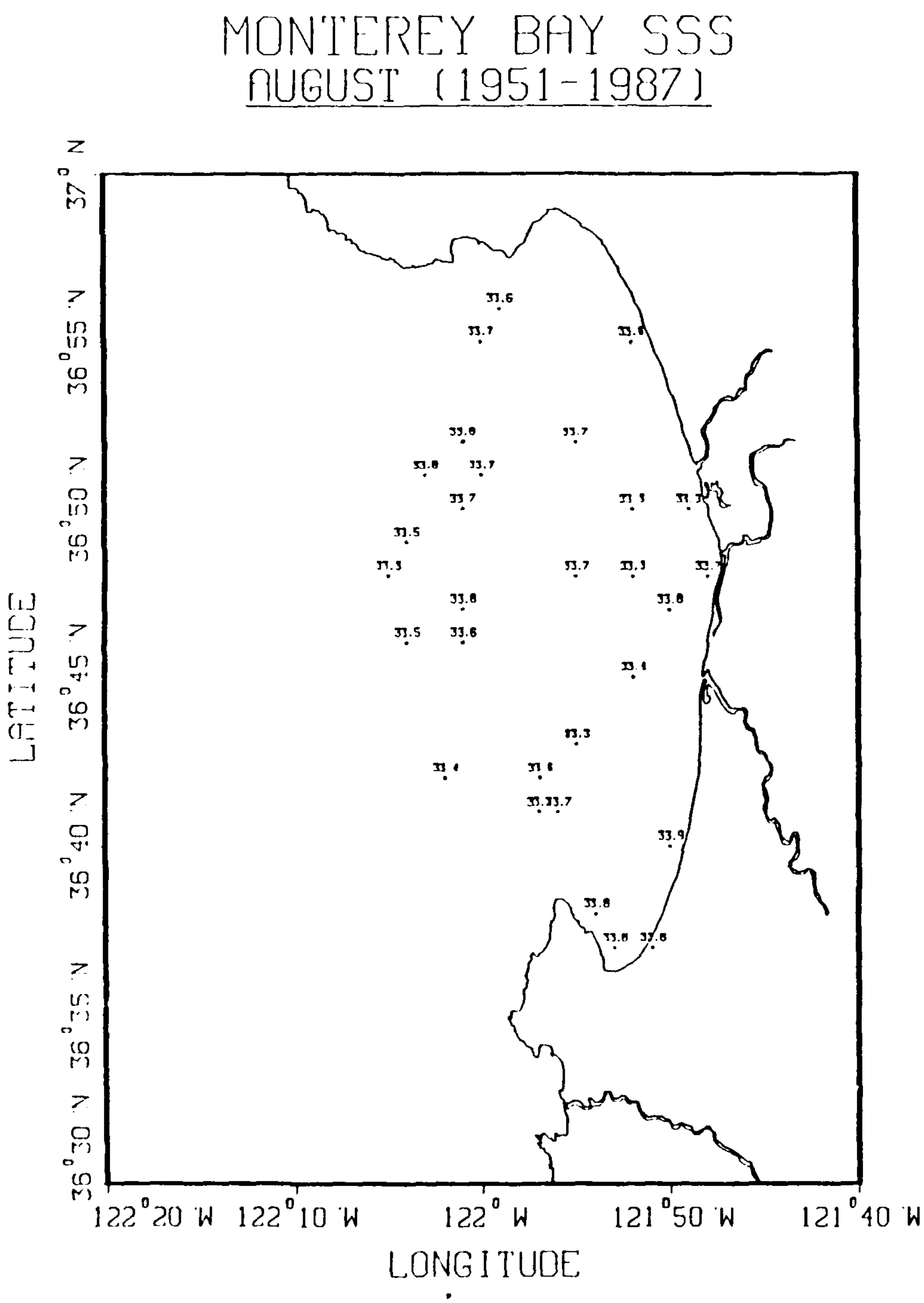

Figure 31 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (AUGUST)

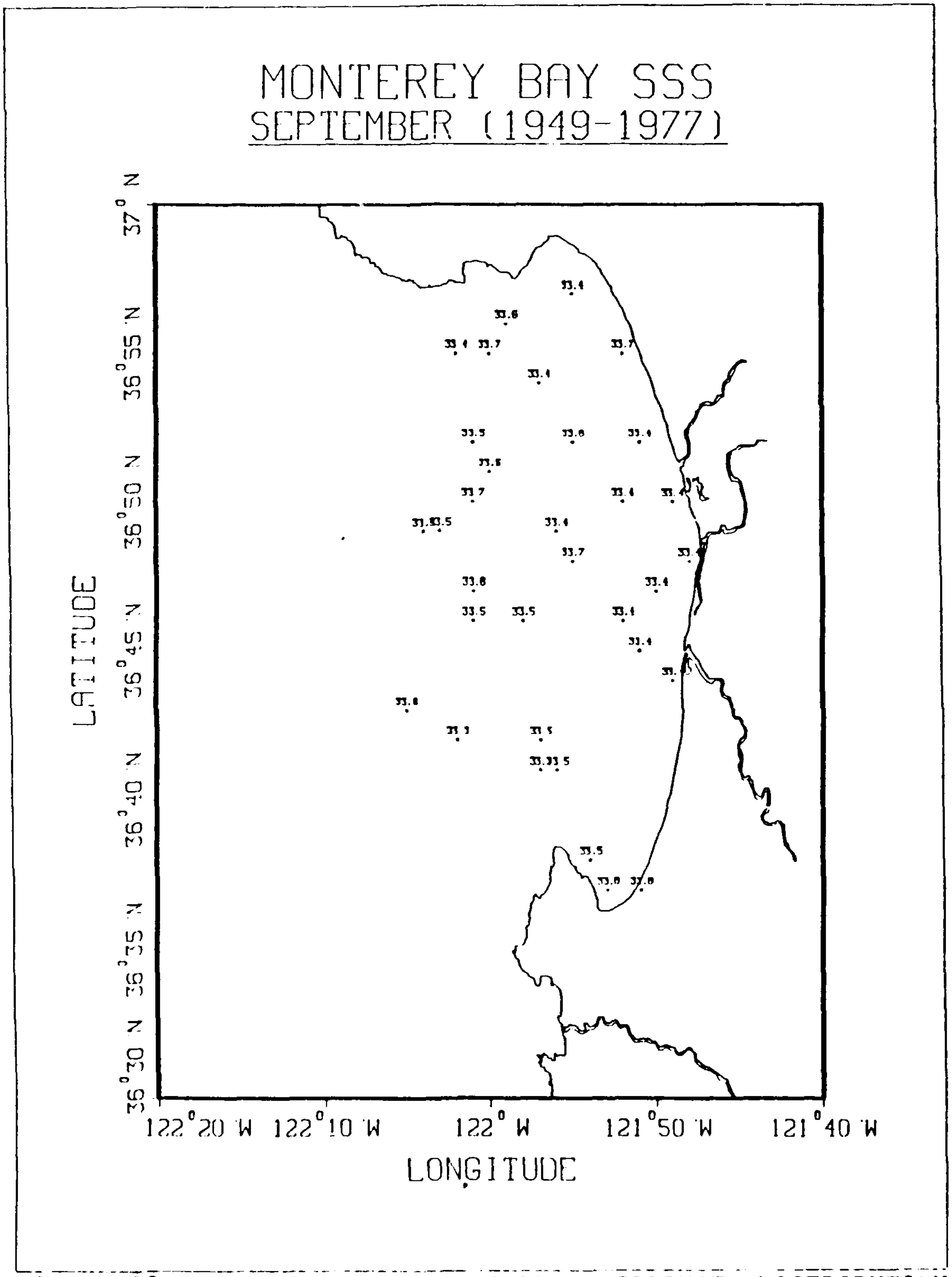

Figure 32 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (SEPTEMBER)

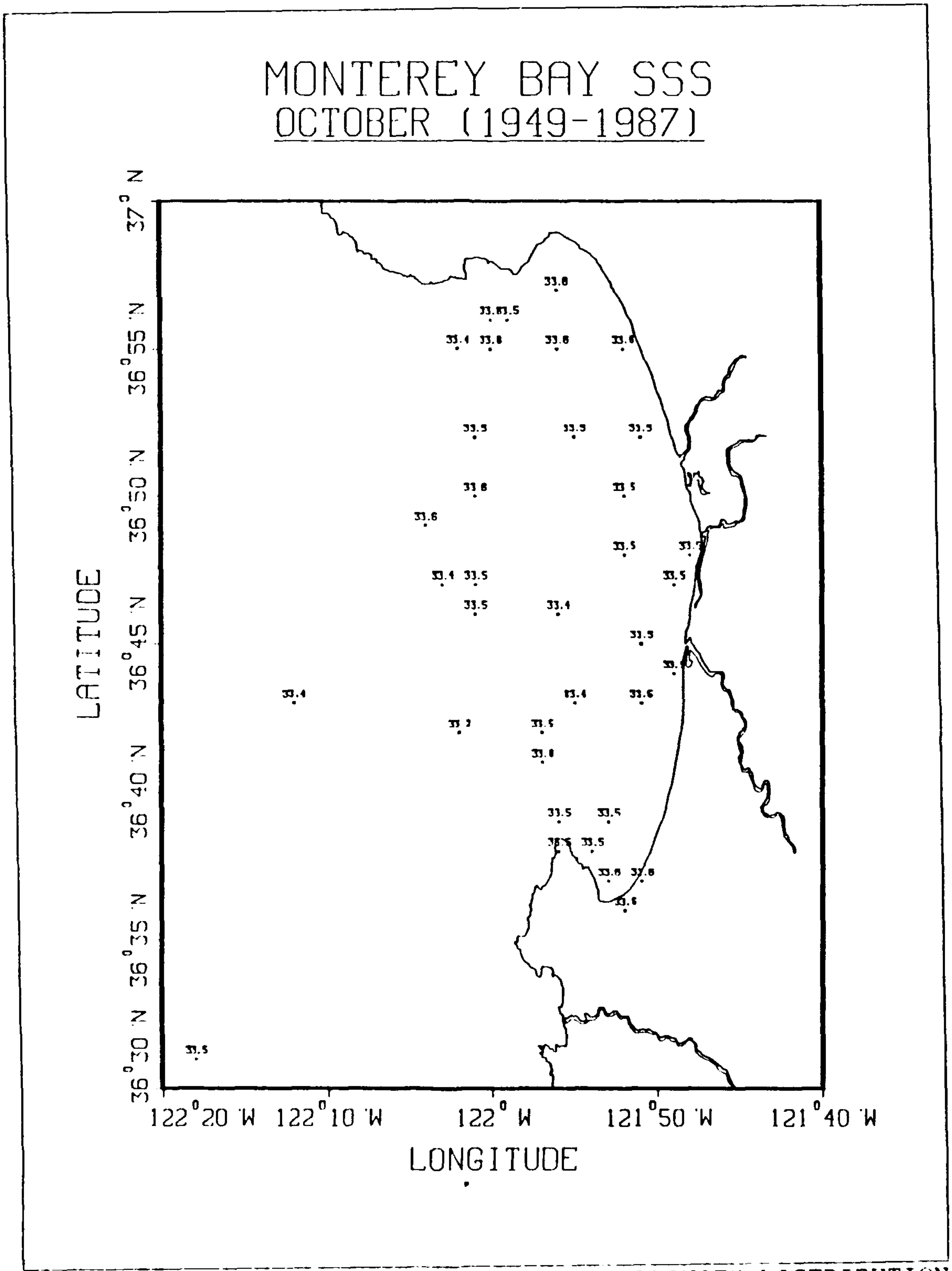

Figure 33 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (OCTOBER)

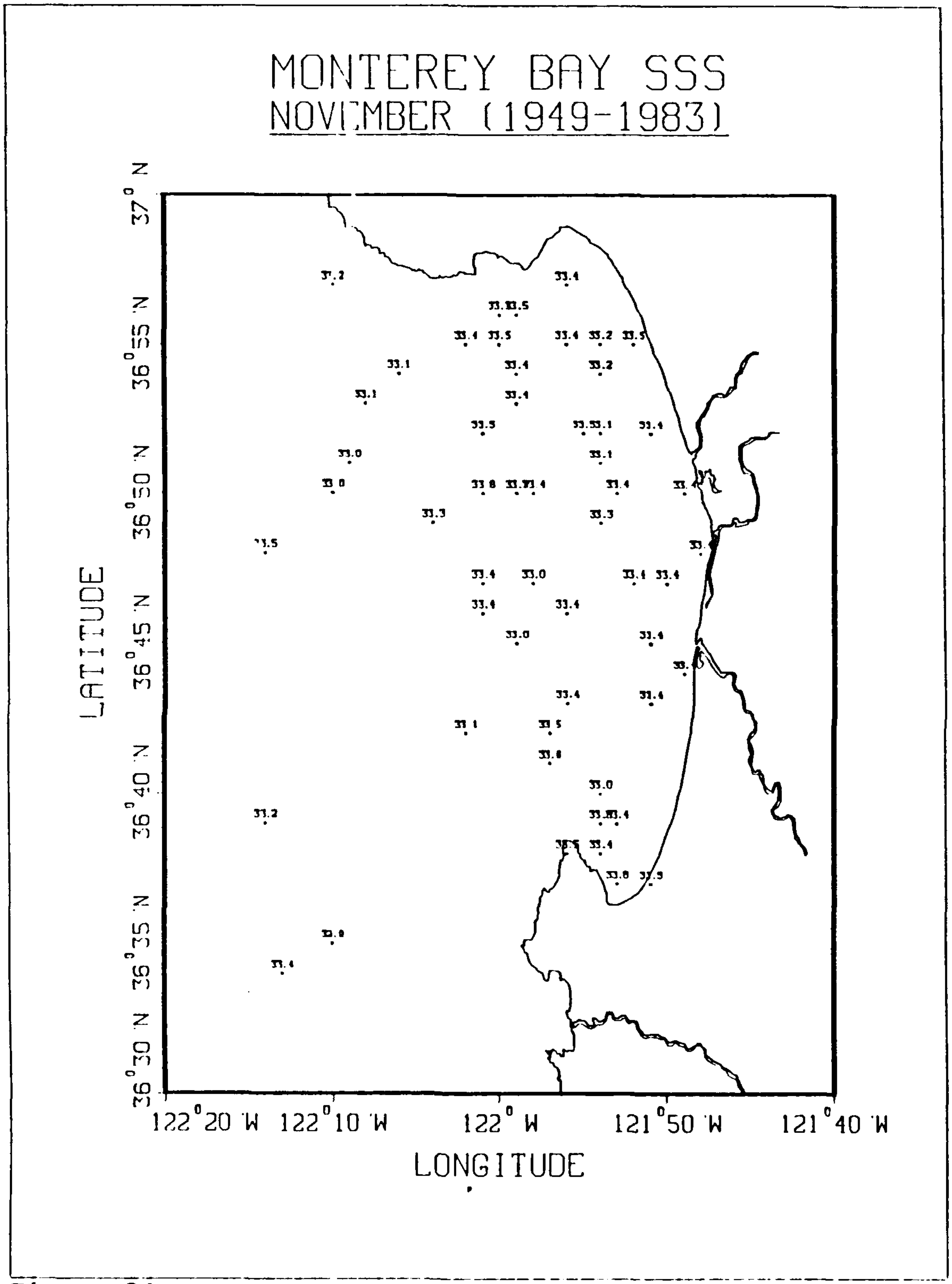

Figure 34 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (NOVEMBER)

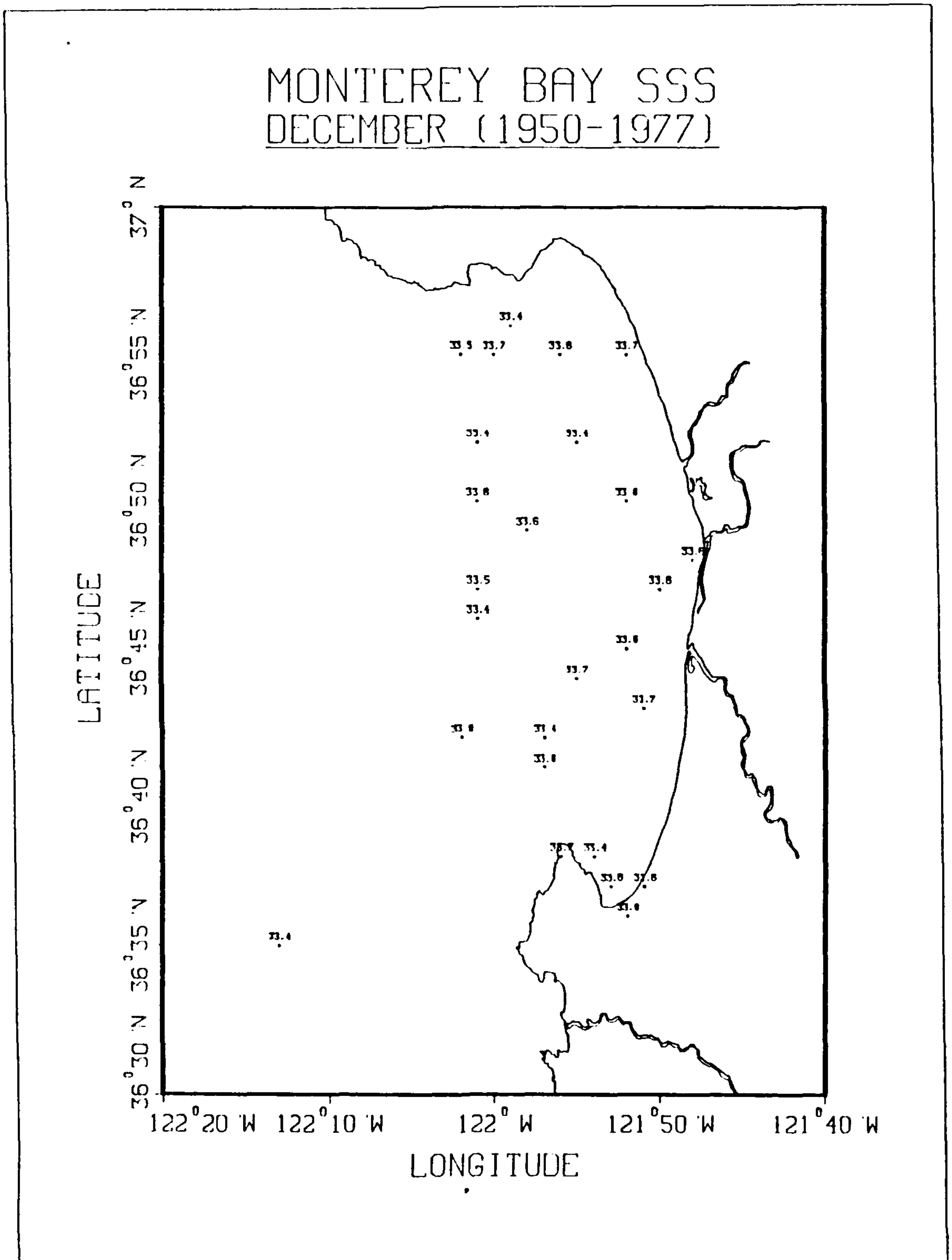

Figure 35 MONTHLY MEAN SEA SURFACE SALINITY DISTRIBUTION (DECEMBER)

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